# FISHERY ASSESSMENT REPORT

# TASMANIAN GIANT CRAB FISHERY - 2005/06

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This assessment of the giant crab fishery is produced by the Tasmanian Aquaculture and Fisheries Institute (TAFI) and uses input from the Crustacean Assessment Working Group (CAWG).

CAWG met on 30 October 2006 to consider the draft assessment report and provide input into the assessment. The Working Group participants were:

| | |
|---|---|
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## Executive summary

This assessment of the Tasmanian giant crab fishery resource relates to the fishery for the period from 1 March 2005 to 28 February 2006 and provides forecasts of the likely response of the fishery to the total allowable commercial catch (TACC) set at a range of values.

Total catch reported in logbooks for the 2005/06 season was 64.6 tonnes, representing 104% of the 62.1 tonne TACC[1]. This contrasts with the previous quota year, when only 52.7 tonnes were caught and the Limit Reference Point, set at 90% of the TACC, had been exceeded.

Total fishing effort in the 2005/06 quota year was slightly higher compared to 2004/05 as a result of increases on the west coast.

The reference point relating to a statewide decline in catch rates of successive years was not exceeded, as catch rates increased slightly in the 2005/06 quota year. However, they still remain near record lows. Regionally, the catch rate reference point for the west coast was exceeded even though catch rates were similar to last year. The triggering was caused by a substantial drop in the 2004/05 quota year combined with a minor decrease in the most recent year, leading to a total decline of -36.4% over the 2-year period. In contrast, catch rates on the east coast showed some improvement after many years of stability at low levels.

Bycatch of crabs by lobster fishers in the 2005/06 season was not of concern for the giant crab fishery, with the reported catch of only 66 kg being well below the reference point of 5 tonnes.

Reference points relating to the weight structure of the catch landed at processors (the variation in the proportions of the catch above 5 kg or below 3 kg) were not assessed, because no weight information on the ‘size splits’ from the processors was available for this assessment.

The size-based stock assessment model was able to generate acceptable fits to both catch rate and length frequency data. As expected, this showed that:

- There has been a decline in the stock size as the fishery developed, with the exploitable biomass dropping from 1440 tonnes at the start of the fishery to about 260 tonnes in 2005/06. This equates to about 18% of the original exploitable biomass.
- Total biomass and egg production have dropped to 35% and 41% respectively. This level of egg production is high relative to most fisheries.

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[1] The quota allocation system and the logbook recording do not correspond completely. The quota is considered only when the animals are sold or landed, while an entry in a fisher’s logbook records the date of capture, and it is quite common for a fisher to hold animals for extended periods (Gardner 1998).

- Harvest rates increased from 0.21 in 2004/05 to 0.25 in the recent year. This was due to the higher catch, while estimated exploitable biomass remained fairly steady. Given the high level of harvest rate at low levels of biomass, the stock is likely to remain stable or rebuild only slowly at the current TACC.

The risk assessment projections of the model suggested that the current TACC of 62.1 t has a greater than 80% chance of resulting in slow rebuilding of exploitable biomass over the next 5 to 10 years, assuming no significant external impacts such as an increase in trawl interactions. Conversely, under a TACC of 103.5 tonnes, there is only a 50% chance of rebuilding of exploitable biomass over the next 10 years (this is equivalent to a 50% chance that the stock will decline over the next 10 years). Egg production is less sensitive to change in TACC (and thus harvest rate) as females mature below the size limit. Thus, even higher TACCs of 103.5 t appear likely to lead to stability in reproductive output (80% probability).

**Table 1.** Summary performance indicator assessment for giant crab.

| Performance indicator | Reference point | Exceeded | Status in 2005/06 |
|---|---|---|---|
| Total yearly catch | Yearly catch < 90% of TACC | No | 100% of TACC taken |
| Statewide commercial catch rates | Decline in two consecutive years | No | Increased in 05/06 season |
| Regional commercial catch rates | Total decline by 20% in 2 years | Yes | East +32%, West -36% |
| Bycatch by lobster fishers | Catch > 5 tonnes | No | 66 kg taken |
| Proportion of catch over 5 kg | Varies >30% from reference year | N/A | Data unavailable |
| Proportion of catch below 3 kg | Varies >30% from reference year | N/A | Data unavailable |

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# 1. Introduction

This assessment of the Tasmanian giant crab fishery resource contrasts the fishery against performance indicators defined in the giant crab management plan (DPIWE 1999) for the period from 1 March 2005 to 28 February 2006. Other information is provided to assist in assessing the state of the resource including results from the giant crab stock assessment model, and forecasts of the likely outcome of alternative total allowable commercial catches (TACC).

The commercial fishery for giant crab began in Tasmania in the mid 1990s after a live export market to Melbourne, Sydney and Asia was established (Gardner 1998). Giant crabs had previously been landed as byproduct of rock lobster fishers operating in deeper waters but were generally regarded more as a nuisance than a target. Once giant crab became a targeted species, catches increased dramatically. By 1994/95, total reported catch in Tasmanian waters peaked at 291 tonnes (Figure 1). While some of this catch may be attributable to over-reporting of catch in anticipation of a change in management (moving to quota), it is certain that large quantities of crabs were taken as the virgin stock was being fished down.

By the end of the 1997/98 the total catch had fallen to just 110 tonnes and some concern were expressed that the giant crab resource was being over-exploited. Quota management was introduced to the associated rock lobster fishery at this time and there was concern that the crab fishery could create an effort sink. A giant crab management plan was introduced in November 1999 with an Individual Transferable Quota (ITQ) system and an initial TACC of 103.5 tonnes. The quota year mirrored that for rock lobsters running from 1$^{st}$ of March to the end of the following February (DPIWE 1999). Along with the introduction of a TACC, a maximum size limit was set at 215 mm carapace length for both males and females, while the minimum legal length of 150 mm for both sexes, introduced in 1993, was retained.

In response to further declines in catch per unit effort (CPUE) across much of the fishery and poor performance against indicators in the 2002/03 assessment (Gardner *et al.* 2004), the TACC was further reduced to 62.1 tonnes for the 2004/05 quota season. The same quota remained in place for the 2005/06 quota season.

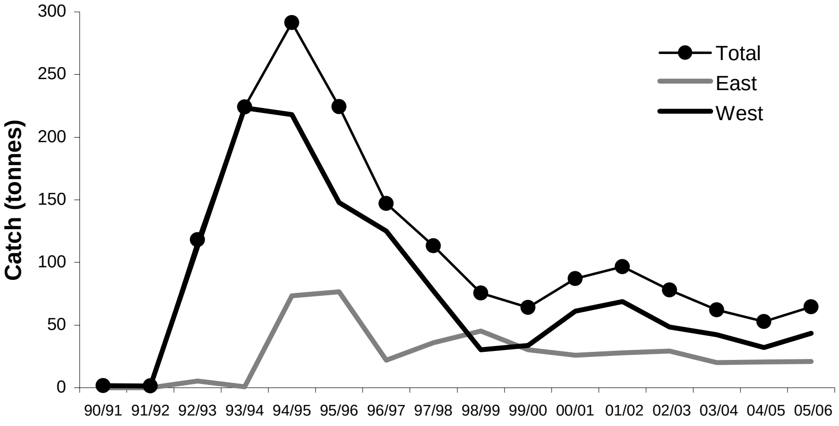

**Figure 1.** Historical giant crab catches in Tasmania. Catches in 1998/99 and 1999/00 were from partial fishing years due to an extended seasonal closure. East and west are divided by longitude 147ºE.

# 2. Management objectives and strategies

The Tasmanian giant crab management plan was introduced in 1999 (DPIWE 1999) and provides the regulatory framework for the commercial fishery. The plan contains the following objectives, strategies and performance indicators.

## 2.1 Major objectives

- Maintain fish stocks at optimum sustainable levels by constraining the total catch and the size of individual giant crabs taken by the commercial sector;
- Sustain yield and reduce incidental fishing mortality by taking fish at a size likely to result in the optimum yield from the fishery, protecting under-size giant crabs, and minimising incidental fishing mortality as a result of fishing operations;
- Manage commercial fishing interactions by mitigating any conflict that results from competition between different fishing methods for access to shared fishing grounds;
- Provide socio-economic benefits to the community;
- Provide high quality products.

## 2.2 Primary Strategies

- Limit the targeted commercial catch by setting a total allowable commercial catch (TACC) and using individual transferable quotas (ITQs) to allocate proportions of the TACC;
- Limit access to by-catches of giant crabs.
- Maintain minimum and maximum size limits and closures of the fishery for female giant crabs during the peak spawning period to conserve egg production, restrict fishing mortality on spawning or berried female giant crabs, and ensure a proportion of large males and females are returned to the water;
- Maintain escape gaps to reduce incidental fishing mortality;
- Restrict the number of giant crab fishing vessels in the fishery and the number of giant crab traps that can be used from individual fishing vessels.

## 2.3 Performance Indicators

The giant crab management plan identifies (but does not restrict) a number of performance indicators that are used to define reference ranges, which are deemed to represent the normal variation of the stocks and fishery. When the observed value of a performance indicator falls outside this range, a limit reference point or trigger point is said to have been exceeded, implying that some management action may be required. Reference points are exceeded when one or more of the following criteria are met:

- The total yearly catch does not exceed 90% of TACC in any year;
- Catch per unit effort (CPUE) for the State declines for two consecutive years;
- Catch per unit effort (CPUE) for any region declines by a total of 20% in two years;
- The bycatch of giant crabs taken by rock lobster fishers exceed 5 tonnes in any year;
- The proportion of the catch above 5 kg or below 3 kg varies by more than 30% compared to the 1996/97 distribution.

# 3. Fishery assessment

## 3.1 Evaluation of reference points

### 3.1.1 Commercial catch

Total catch reported in logbooks for the current assessment period was 64.6 tonnes, representing 104% of the 62.1 tonne total allowable commercial catch (TACC). This was in contrast to the previous quota year, when only 52.7 tonnes were caught and the catch limit reference point, set at 90% of the TACC, was exceeded (Table 2, Figure 2).

It is important to note that the quota allocation system and the logbook recordings listed in Table 2 do not correspond completely. The quota is considered only when the animals are sold or landed. In contrast, an entry in a fisher's logbook records the date of capture, not date of sale, and it is quite common for a fisher to hold animals for extended periods until the market price improves (Gardner 1998).

**Table 2.** Catch totals in tonnes by quota year (March to February) from 1989/90 until present as reported in logbook returns. East and west are defined as either side of longitude 147ºE.

| Quota year | Total | East | West |
|---|---|---|---|
| 1989/90 | 0.2 | 0.1 | 0.1 |
| 1990/91 | 1.7 | 0.1 | 1.6 |
| 1991/92 | 1.5 | 0.1 | 1.4 |
| 1992/93 | 118.2 | 5.4 | 112.8 |
| 1993/94 | 224.2 | 0.8 | 223.4 |
| 1994/95 | 291.4 | 73.5 | 217.9 |
| 1995/96 | 224.3 | 76.6 | 147.8 |
| 1996/97 | 147.0 | 21.9 | 125.1 |
| 1997/98 | 113.3 | 35.9 | 77.4 |
| 1998/99 | 75.6 | 45.2 | 30.4 |
| 1999/00 | 64.2 | 30.3 | 33.9 |
| 2000/01 | 87.1 | 25.9 | 61.2 |
| 2001/02 | 96.6 | 28.0 | 68.6 |
| 2002/03 | 78.0 | 29.4 | 48.5 |
| 2003/04 | 62.3 | 20.0 | 42.3 |
| 2004/05 | 52.7 | 20.7 | 32.1 |
| 2005/06 | 64.6 | 21.0 | 43.6 |

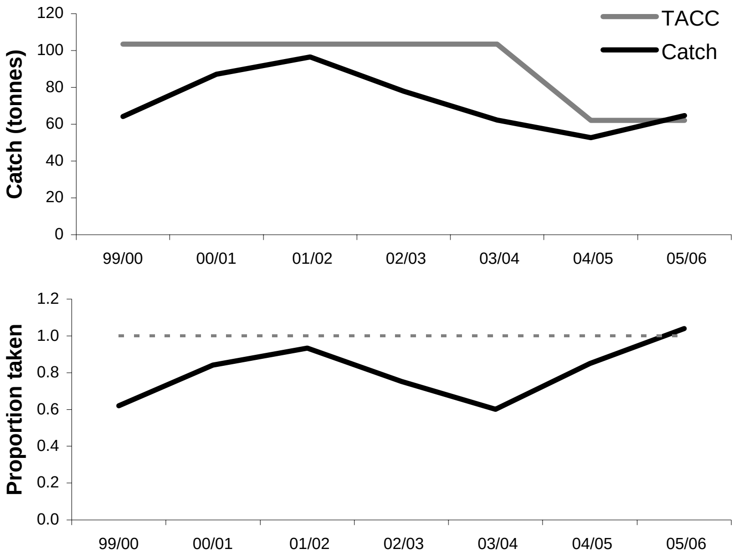

**Figure 2.** Total catches from logbook records and TACC since quota management was introduced (top), and the proportion of the TACC caught in each year (bottom). The dashed line marks 100%.

The catch in the current assessment period comprised 21.0 tonnes (32%) taken from the east coast and 43.6 tonnes (68%) taken from the west coast. This is within the historical range exhibited since the introduction of quota, after relative and absolute catches from the west coast have been low during the last quota year (Table 2, Figure 3). The ratio in catch from the two coasts appears to have stabilised over the last few years as crab fishing businesses have stabilised.

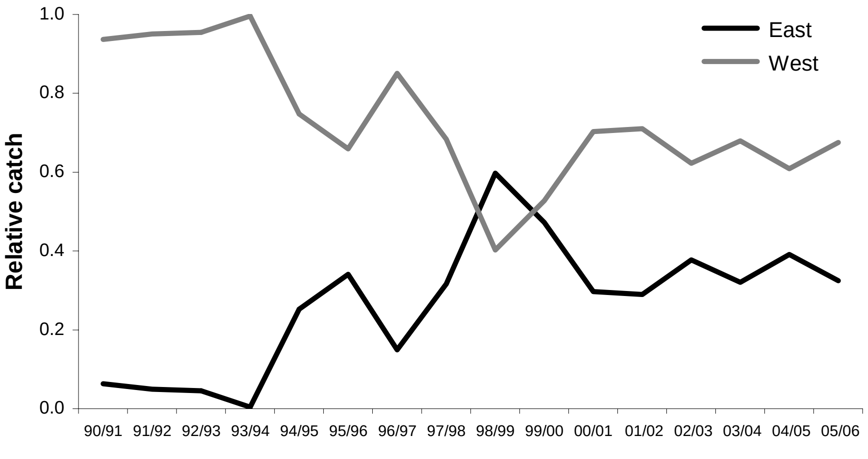

**Figure 3**. Relative catches coming from the east and west coast in each quota year.

### 3.1.2 Commercial effort

Total fishing effort in the 2005/06 quota year was slightly higher compared to 2004/05. This was mainly driven by a strong increase on the west coast, while the east coast has seen some reduction in effort (Figure 4).

Seasonal patterns of effort changed with slightly increased effort in the early part of the quota year when compared to recent years, but similar levels of effort between winter and summer (Figure 5). When compared with recent years, east coast effort was uncharacteristically high in the first four months of the assessment period, but tended to be lower in the latter half of the season (Figure 6). On the west coast, effort was relatively high from March to May and again in January and February. These trends in seasonal effort tend to be a function of activity in other fisheries, especially scallop and rock lobster as crab fishers typically operate across these different fisheries.

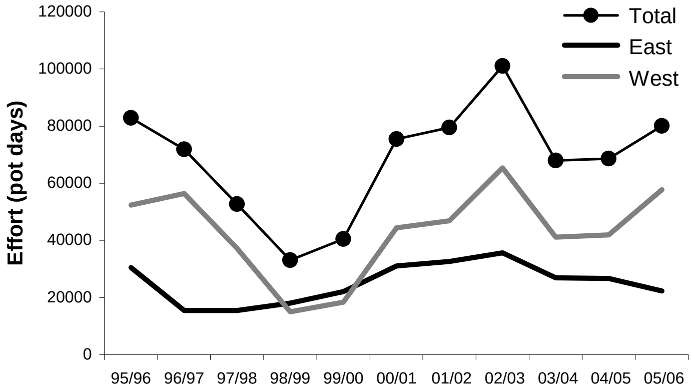

**Figure 4.** Total effort (pot days) and effort overall and for the east and west coast by quota year since 1995/96. 1998/99 and 1999/00 were partial fishing years.

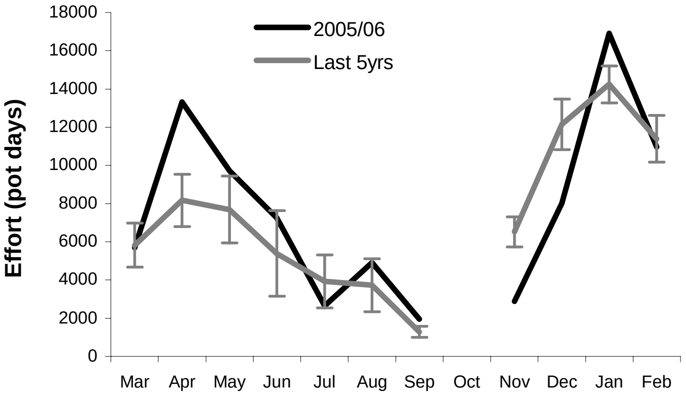

**Figure 5.** Seasonal trends in effort for 2005/06 (black line) and annual average for the preceding 5 years (grey line) including standard error bars.

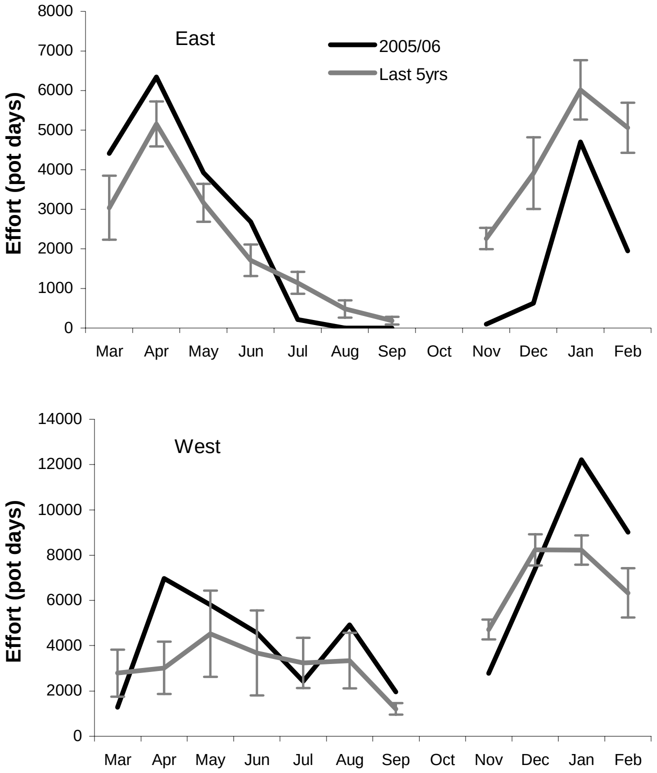

**Figure 6.** Seasonal trends in effort for the east and west coast in the 2005/06 quota year (black line) and average for the 5 previous yeas (grey line) including standard error bars.

### 3.1.3 Commercial catch rates

Two reference points relate to changes in commercial catch per unit effort (CPUE), which are drawn from commercial logbooks. Logbook data prior to January 1995 do not include a measure of effort (number of traps), so only data since the 1995/96 quota year can be used for calculating catch rate. The data have been “cleaned” for a range of factors:

- Misreporting of effort appeared to be a common problem early in the fishery and records that were know to be false or appeared unreliable (*e.g.* low trap numbers or extreme catch rates) have been excluded from the analyses.
- Crabs are often taken incidentally to lobster fishing and catch rates under these situations are believed to be quite different to when crabs are targeted. The analysis of catch rates here was restricted to targeted effort. Fishers note in the current logbooks whether their effort is targeted towards giant crab, but this was not the case prior to 2000. As an alternative approach and to perform an analysis for the whole the period since 1995/96, logbook data were restricted to vessels which had been in the fishery for a minimum of 2 years with a median catch of at least 1000 kg per year during that period. This selected experienced fishers with vessels and gear more suited to crabs who take most of the overall crab catch, while fishers with small catches, that directed most of their fishing effort towards lobsters and tended to have lower catch rates, were excluded.

Catch rates were estimated as kilograms per pot days for each record in the database as:

$$\text{CPUE} = \frac{\text{Weight of catch (kg)}}{\text{Number of traps} \times \text{Soak time}} \tag{3.1}$$

where pot days are defined as the number of traps multiplied with number of days the traps are in the water before being hauled (soak time). Soak time capped at 7 days, based on the belief that soak times greater than 7 days do not lead to increases in catch, resulted in reduced normality of the (log-transformed) data and was not used.

The geometric mean, rather than the arithmetic mean, of all valid individual daily catch records was calculated to generate the catch rate statistics, since catch rate data were log-normally distributed. The geometric mean is the $n^{th}$ root of the product of the individual rates ($y_i$), which is equivalent to computing the arithmetic mean of the natural logarithm of each number and then taking the exponent:

$$GM_{\bar{y}} = \exp\left[\frac{1}{n}\left(\sum \ln\left(y_n\right)\right)\right] \tag{3.2}$$

It should be noted that catch rates calculated in this manner may differ slightly from the more simplistic approach of using the arithmetic mean (ie dividing total catch by total effort). The geometric mean has the advantage of being less affected by the few observations that are skewed very high, which often happens with log-normally distributed catch data.

### *Annual commercial catch rates*

The reference point relating to a statewide decline in catch rates in successive years was not activated, as CPUE increased slightly in the 2005/06 quota year (Figure 7). However, statewide CPUE had been at its lowest point in the previous year and still remained low in 2005/06. As a comparison, CPUE based on all data was substantially lower in the late 1990s than the current CPUE, which is based on a selection of targeted effort for vessels that have been in the fishery for a minimum of 2 years with a median catch of at least 1000 kg per year. This indicates that a lot of bycatch and explorative fishing occurred earlier in the fishery, which is uninformative for CPUE trends and thus should not be used for the interpretation of CPUE trends.

Regionally, the CPUE limit reference point for the west coast was exceeded (-36.4% over the 2-year period) after a substantial drop in the previous quota year, although catch rates have been stable since. Catch rates on the east coast showed some improvement after many years of stability at low levels (Figure 8, Table 3).

**Table 3.** Targeted catch per unit effort (CPUE) overall and on the east and west coast for the 2005/06 quota year relative to CPUE 5, 2 and 1 year ago. The reference point relates to the 2-year period.

| | Change in catch rates (in %) compared to | | |
|---|---|---|---|
| | 5 years | **2 years** | Last year |
| Total | -30.1 | **-16.8** | 11.6 |
| East | 8.1 | **32.3** | 37.6 |
| West | -48.2 | **-36.4** | -0.2 |

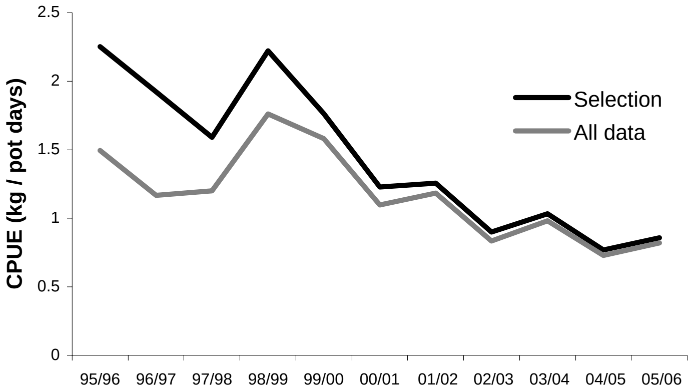

**Figure 7.** Trends in statewide annual catch per unit effort (geometric mean) since 1995/96 by quota year. The black line is based on a selection of targeted effort for vessels that have been in the fishery for a minimum of 2 years with a median catch of at least 1000 kg per year, while the grey line is based on all records.

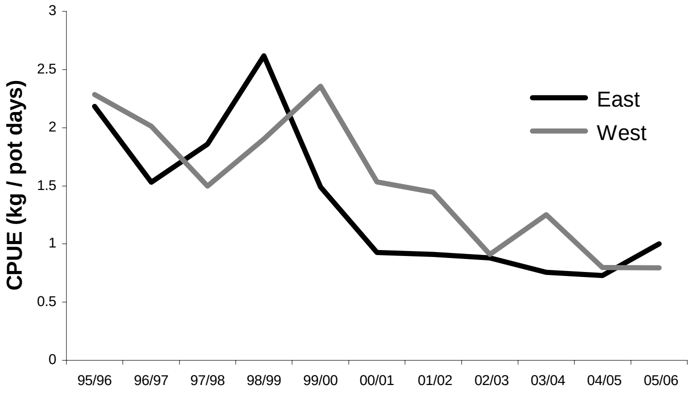

Figure 8. Trends in targeted annual catch per unit effort (geometric mean) for the east and west coast since 1995/96 by quota year.

### *Seasonal catch rates*

While there are no management reference points relating to seasonal changes in regional catch rates, this analysis provides additional details concerning the mechanisms behind observed changes in annual catch rates. Seasonal patterns in CPUE showed that catch rates in the 2005/06 quota season were far more variable throughout the year than the average of previous years (Figure 9). Catch rates tended to be lower than usual in May and the subsequent summer months, yet catch rates were higher in winter months. Higher catch rates in winter months are viewed positively by the industry, since beach prices are typically higher during winter. This is also a positive pattern for the resource as increased catch rates in winter tend to lead to increased catch in winter when females cannot be landed.

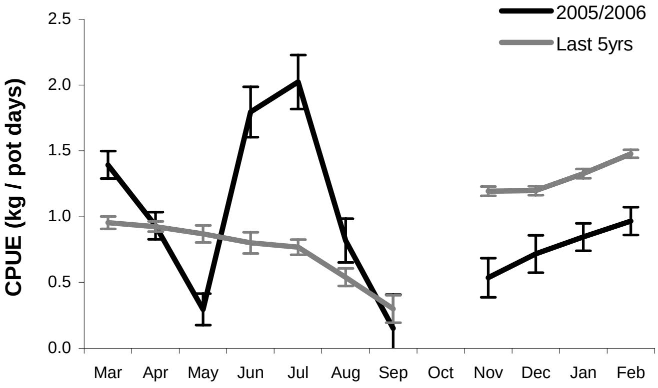

**Figure 9.** Trends in statewide seasonal catch per unit effort (geometric mean for targeted data) in the 2005/06 quota year (black line) and for the last 5 quota years (geometric mean, grey line) with standard error bars.

The high statewide catch rates in March were mainly a function of high catch rates at this time on the east coast, while the catch rates from the west coast underpinned the high catch rates in the winter months and low catch rates in May and the summer months (Figure 10).

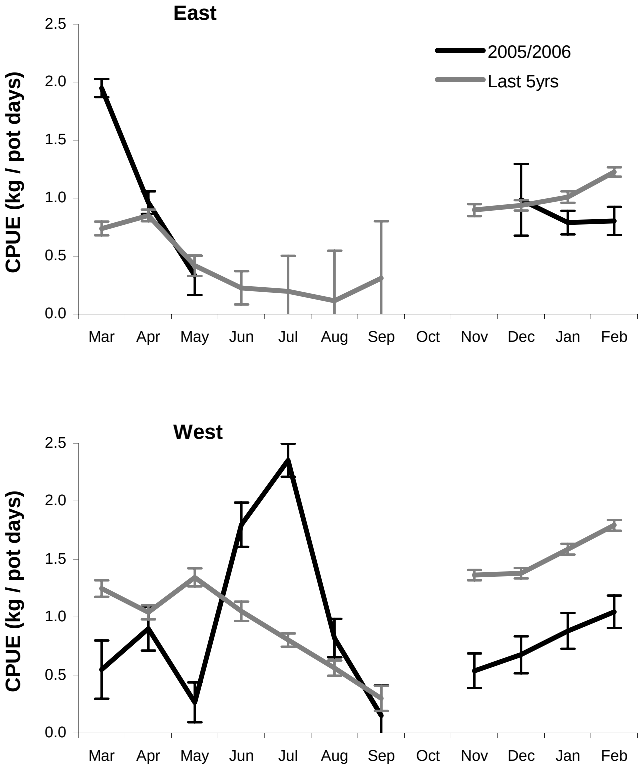

**Figure 10.** Seasonal trends in catch per unit effort (geometric mean for targeted data) for the east and west coast in the 2005/06 quota year (black lines) and for the last 5 quota years (geometric mean, grey line) with standard error bars.

### 3.1.4 Bycatch from the lobster fishery

The reference point relating to bycatch of crabs by the lobster fishery is set at 5 t, which represents 8% of the current TACC. Since the introduction of quota management, bycatch from the lobster fishery has not exceeded 1.1 t (in 2000/01) and was just 66 kg or 0.1% of the landed giant crab catch in the 2005/06 assessment period (Figure 11).

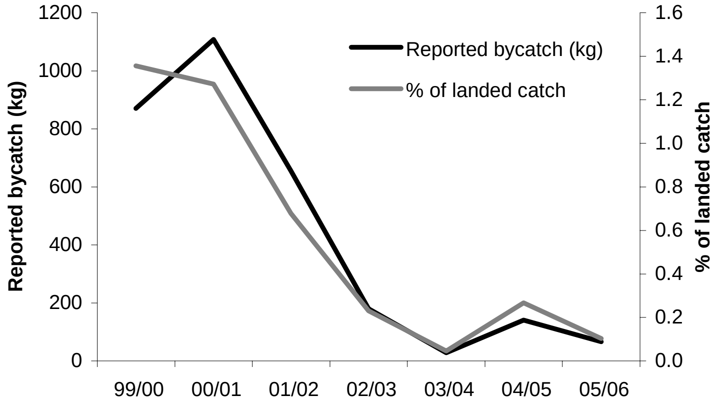

**Figure 11.** Total reported bycatch from the rock lobster fishery and percentage of the total giant crab catch.

### 3.1.5 Weight and size distribution of commercial catch

The two reference points relating to the weight distribution of the commercial catch, *i.e.* the variation in the proportions of the catch above 5 kg or below 3 kg, could not be assessed, because no weight information was available for this assessment. Up until 2002/03, limited weight information was available for assessment purposes based on the ‘size splits’ obtained from processors. These splits are the size groupings by which processors determine the price of crabs. However, these data had to be interpreted with caution, since fishers were able to select (upgrade) or target smaller crabs that have been more highly valued, by varying the depth at which they fished.

Limited data on the size distribution of the catch can now be obtained directly from logbook returns, as fishers record the number of legal-sized and undersized crabs. While catch rates for numbers of males and female crabs have generally dropped over recent years, the catch rates of undersized crabs has increased on the west coasts (Figure 12). This latter trend is a positive sign for the fishery as it suggests increased recruitment in the future. However, this trend could be also an artefact of behavioural interactions between crabs around traps. If larger animals aggressively inhibit small animals from entering traps as it has been documented in the Tasmanian lobster fishery (Frusher *et al.* 2003), then undersized crabs may now appear more abundant when catch rates of large crabs decrease and smaller crabs are more likely to enter traps. On the east coast, a degree of ‘mirroring’ between catch rates of undersized and legal-sized females is apparent that is consistent with such a behavioural mechanism (Figure 12). Underlying these annual trends is a strong seasonal pattern of sex ratios within the retained catch (Figure 13) with either overall lower catch rates for females or berried females being discarded during winter months between June and October.

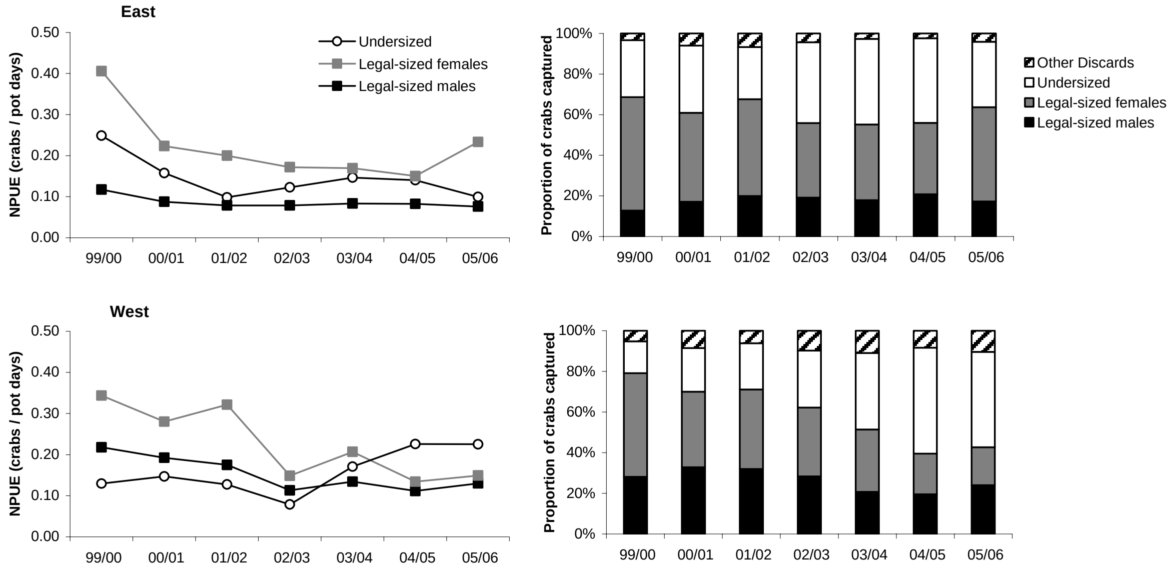

**Figure 12.** Number of crabs per unit effort (pot days) on the east and west coast (left) for undersized crabs (open circles), legal-sized females (filled grey squares) and legal-sized males (filled black squares); and overall proportion of captured crabs that are legal sized females or males, undersized or other discards (right).

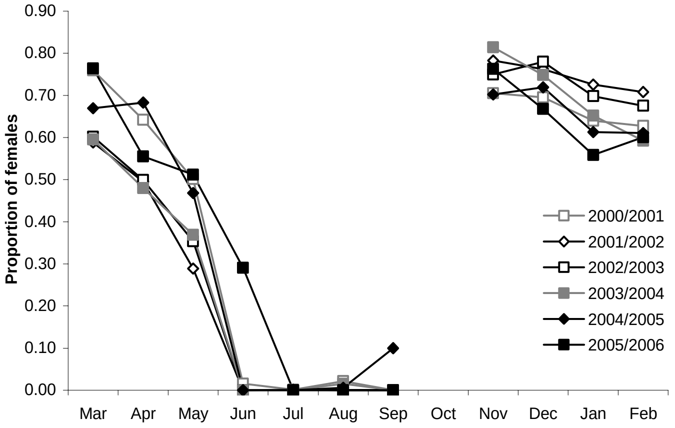

**Figure 13.** The proportion of retained giant crabs that were female for each month within a quota year. Note these proportions are based on number of individuals, not weight, and that a proportion of 0.75 equates to catch comprised of three females for every male. The season is closed in October.

A voluntary measurement system using digital callipers and data loggers also provides measures of the size composition in the catch. Fishers measure all catch, not just retained animals, and data are accurate to within a few millimetres. Using this system, over 20,000 crabs have been measured for a number of quota years. These data have been incorporated into the stock assessment model and is presented in Section 3.3.4 of this report (Figure 18).

## 3.2 Assessment of other species caught by the Tasmanian giant crab fishery

### 3.2.1 Bycatch

Bycatch is defined as any non-target species that are caught during fishing operations and subsequently discarded. The best available information on species caught as bycatch comes from surveys conducted in 2001/02, when this information was collected as part of a FRDC project aimed at improving giant crab assessment techniques. The most common species, in order of abundance were the antlered crab *Paromola petterdi*, hermits crabs (*Strigipagurus strigimanus* and *Dardanus arrosor*) and pink ling *Genypterus blacodes*.

An improved system for bycatch reporting was implemented in 2006 to provide bycatch data on an ongoing basis. Fishers were provided with disposable cameras and photographed bycatch from every second trap. Photos are being taken whether there is bycatch present or not. Insufficient data have been collected from the project to present results at this stage, but the project has already expanded our knowledge of taxa included as bycatch. The project has also confirmed previous observations that most traps do not contain bycatch.

**Figure 14.** Bycatch images from the fisher sampling program.

### 3.2.2 Byproduct

Byproduct differs from bycatch as it is retained, for sale, bait or personal consumption. Byproduct is currently reported through the general fish log and catch taken from giant crab traps or rock lobster pots cannot be distinguished. In previous assessment we have attempted to separate giant crab byproduct from that taken by lobster fishers on the basis of depth.

Byproduct in both the rock lobster and giant crab fisheries is under-reported. Only one single event of byproduct (30 kg of magpie perch) has been reported since 2003/04 from traps set in depths over 120 m (Figure 15).

Several sources contribute to the problem of under-reporting. First, many fishers believe that catch only needs to be recorded if it's sold. Secondly, the recording of byproduct in a separate general fish logbook complicates data recording for fishers. Both these problems are being addressed by altering the giant crab logbook to include bycatch, with specific mention of the use of byproduct as bait. A final problem is that that byproduct used for bait or personal consumption cannot be verified. Information collected through bycatch cameras may assist here as assumptions can be made about the fate of certain bycatch (e.g. ling is unlikely to be returned).

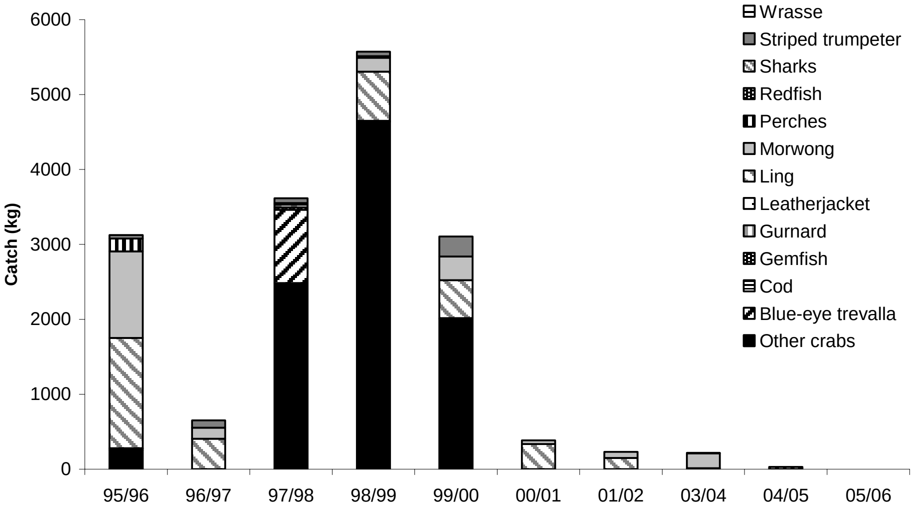

**Figure 15**. Reported scalefish byproduct from the giant crab fishery (pots that were set in depths greater than 120m) since the 1995/96 quota year.

### 3.2.3 Protected Species Interactions

While protected species interactions from the rock lobster fishery, which were considered to be relevant also to the crab fishery, have been reported in previous assessments, interactions specifically with the crab fishery will be recorded for the first time during the 2006/07 fishing season and will be reported in the next assessement.

## 3.3 Stock assessment modelling

### 3.3.1 Introduction

A size-based stock assessment model with an annual time-step was used for the Tasmanian giant crab. It differs from the model for the Tasmanian rock lobster developed by Punt and Kennedy (1997) in a number of ways but mainly by requiring a matrix of years-to-moult accounting for the extremely long intermoult periods that characterize the growth of giant crabs. The giant crab model was developed as part of the FRDC funded project (FRDC 2001/049) entitled 'Developing the tools for long-term management of the giant crab resource: Data collection methodology, stock assessment and harvest strategy evaluation'. Full details of the model and the underlying description of giant crab growth are given in that document and in the Appendix 1.

### 3.3.2 Uncertainties

There are many sources of uncertainty when modelling the stock dynamics of giant crabs that must be kept in mind when considering the management implications of the model outcomes.

One of the biggest sources of uncertainty derives from the description of growth, which is a fundamental component of any size-based stock assessment model. In order to grow, crustaceans like rock lobsters and giant crabs have to go through a moulting process, whereby their old carapace is shed and the new soft exoskeleton expands and then hardens. A stock assessment model, describing the growth of giant crab is more complex than that of rock lobsters because of their prolonged periods between moulting, known as inter-moult periods.

Most Tasmanian rock lobster moult at least once during a year and the stock assessment model describes their growth by summarizing the expected growth of each size class every three months. It was possible to provide such a detailed description of growth because of the extensive tagging of rock lobsters that has occurred around Tasmania. Giant crabs, on the other hand, live far longer than rock lobsters and their inter-moult periods last potentially over ten years. Not only does the moulting growth increment vary with size but so does the inter-moult interval. Therefore, a new model structure was developed to account for these different growth patterns exhibited by giant crabs. While this model is stable, the details of the growth of the largest crabs, *i.e.* most of the legal-sized animals, had to be determined through extrapolation of the details of the growth of smaller giant crabs. Such extrapolation is inherently risky but provides options for exploring the possible growth patterns and their implied stock dynamics.

The model could undergo further refinement. Currently, it treats the whole of Tasmania as a single population, whereas the fishery operates quite distinctly on the east and west coast. It would be a valuable improvement to extend the model to deal with the two coasts independently, although the amount of data available for the east in some year is limited and could result in substantial uncertainty. At the same time, a greater range of growth possibilities will be included in the analyses in an attempt to capture more of the potential uncertainty in the assessment.

### 3.3.3 Methods

Data was available for catches between 1989/90 and 2005/06, although the reported catches in the first three years were all less than one tonne. The model was fitted to standardised catch rates from 1995/96 to 2005/06, and data reflecting the length frequency of the commercial catch between 80-250 mm from most quota years between 1993/94 and 2005/06.

Catch rates obtained from the log books of commercial fishers were used as an index of relative stock abundance through time. However, many other factors can influence catch rates besides the relative stock abundance, including whether fishers were targeting crabs, the location of effort, season, depth of fishing, and skipper. The impact of these factors can be reduced through a process of standardisation using generalized linear models (GLM; Kimura 1981, 1988). The mathematical process of standardisation is described in detail in Appendix 2.

Eleven different models were tested in the standardisation process with two of these providing the best (most parsimonious) correction of catch rate data. Model 10 standardised for the effects of quota year, skipper, depth, month, fishing block, number of traps, plus the interaction between skipper month and block. Model 11 was equivalent except that it had separate interaction terms for skipper with month and month with block.

Standardised catch rates for the State are shown in Figure 16. The standardisation process made only minor changes to trends but does provide useful insight to the last few years. Un-standardised catch rates declined sharply from 2003/04 to 2004/05 but the standardisation process showed that this was largely a function of changes in the fleet, rather than crab abundance. Likewise, the increase in un-standardised catch rate between 2004/05 and 2005/06 was more subdued in the standardised series.

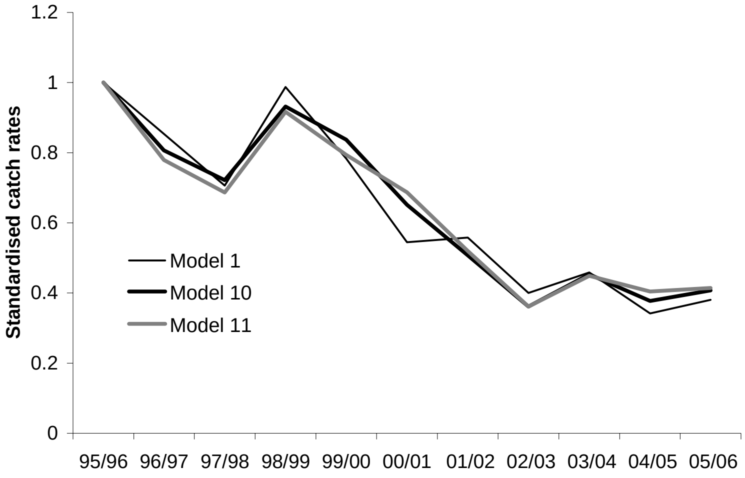

**Figure 16.** Standardised catch rates compared with un-standardised catch rates (Model 1; geometric mean; thin black line). Two standardised catch rate series are shown (Model 10 and Model 11) – each followed the same general trend as the un-standardised series but were typically less volatile. This analysis was restricted to vessels in the fishery for a minimum of 2 years and with a median catch of at least 1000 kg. Note that the values shown here do not correspond to kg / potlift, rather they are scaled to a proportion of the catch rate in the first year of the series (1995/96).

A total of 22 parameters were estimated by the model. These include four selectivity parameters, the average recruitment level, and 17 recruitment residuals defining the predicted deviation from the average recruitment that occurs each year. The model assumed an equilibrium state with average recruitment levels prior to the start of the fishery in 1989/90.

The model outputs include observed and predicted catch rates, harvest rate (the proportion of the legal-sized biomass removed each year), exploitable biomass (the legal-sized biomass at the start of each year), total biomass (biomass of all size classes), egg production and observed and expected length frequencies between 80-250 mm of each year.

A bootstrap procedure on the catch rate data provides an initial estimate of the uncertainty inherent in the assessment. It is likely to underestimate the uncertainty simply because there are so many processes (especially growth) that are only approximately known.

Using the fitted recruitment residuals to define the expected recruitment variation in the future, the stock assessment model permits a projection forward to determine the likely outcomes of different management arrangements in a risk assessment. This assumes that the dynamics as described in the assessment model continue to apply and no new factors come into operation. The model allowed the following options for exploration:

- Varying the total allowable commercial catch (TACC),
- Varying the minimum and maximum legal lengths for either sex,
- Allowing the take of egg-bearing females,
- Varying the length of the closed season for females.

In this present assessment all management options except for the TACC level were kept constant at the present levels. The legal size limits remained at 150 mm minimum legal length and 210 mm maximum legal length for both males and females. An array of different TACC values was examined for their implications for management by projecting the model forward for 10 years under each different harvest strategy. The investigated scenarios included TACCs of 51.8 t, the current 62.1 t, 82.8 t, and 103.5 t, *i.e.* the existing 1035 units set at 50 kg, 60 kg, 80 kg and 100 kg.

### 3.3.4 Fitting the Model

All sources of data influenced the final model fit, with acceptable fits to both catch rate and length frequency data (Figure 17 and Figure 18). Fits to the length frequency data were poor in some years but these generally coincided with relatively small sample sizes.

The large catches reported leading up to 1994/95 led to a significant decline in the predicted stock size. The model estimated that the exploitable biomass declined from about 1440 tonnes in at the start of the fishery to about 260 tonnes in 2005/06. This is a decline to about 18% of the original exploitable biomass. At the same time, total biomass and egg production dropped to 35% and 41% respectively. Harvest rates were generally high, increasing from 0.21 in 2004/05 to 0.25 in the recent year. This was due to the higher catch, while exploitable biomass remained fairly steady. Given the high levels of harvest rate at low levels of biomass, stock rebuilding is needed.

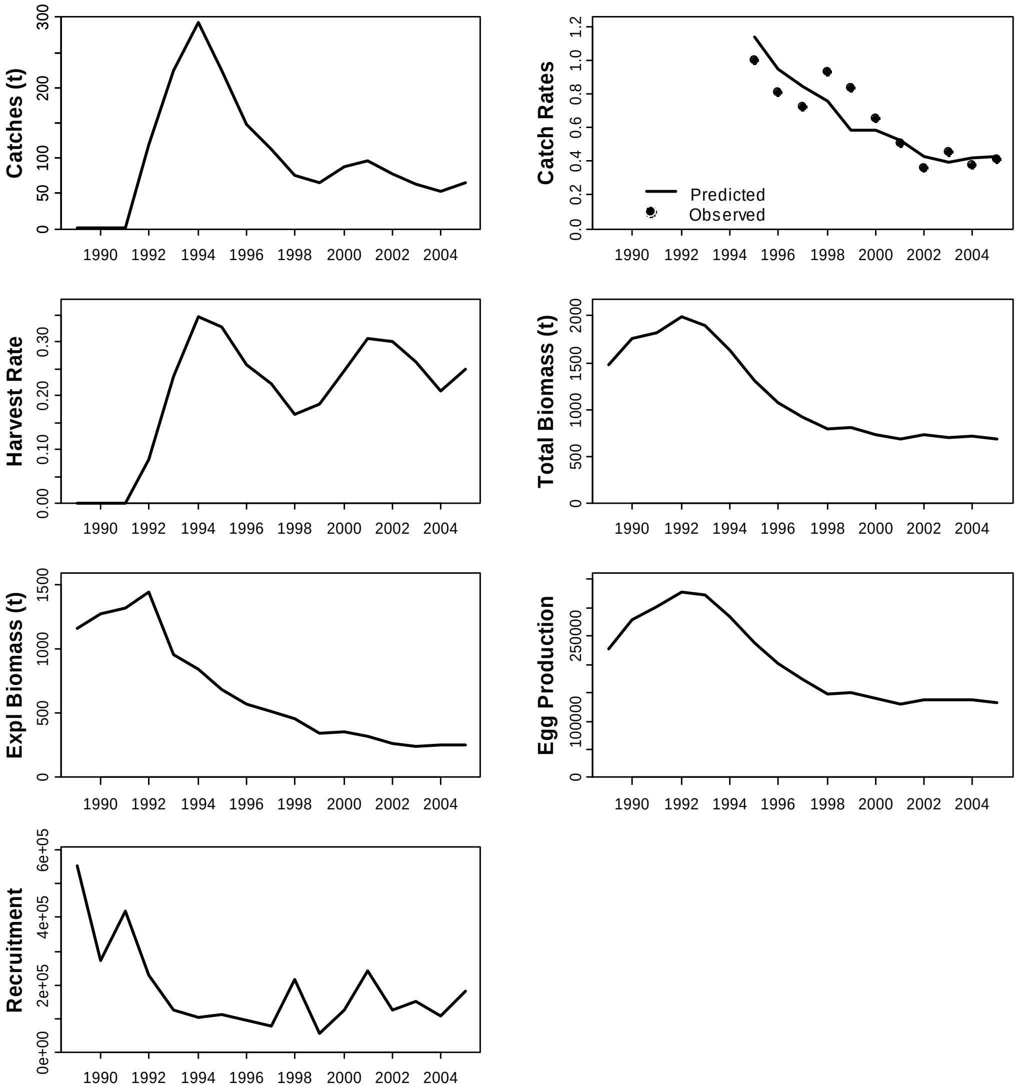

**Figure 17**. Results of the model fitted to the observed data between 1989/90 and 2005/06 (first year of quota year given). Observed catch, observed standardised (black dots) and fitted predicted catch rates (line), and estimated annual harvest rates, total biomass and exploitable biomass at the start of each quota year, egg production and recruitment.

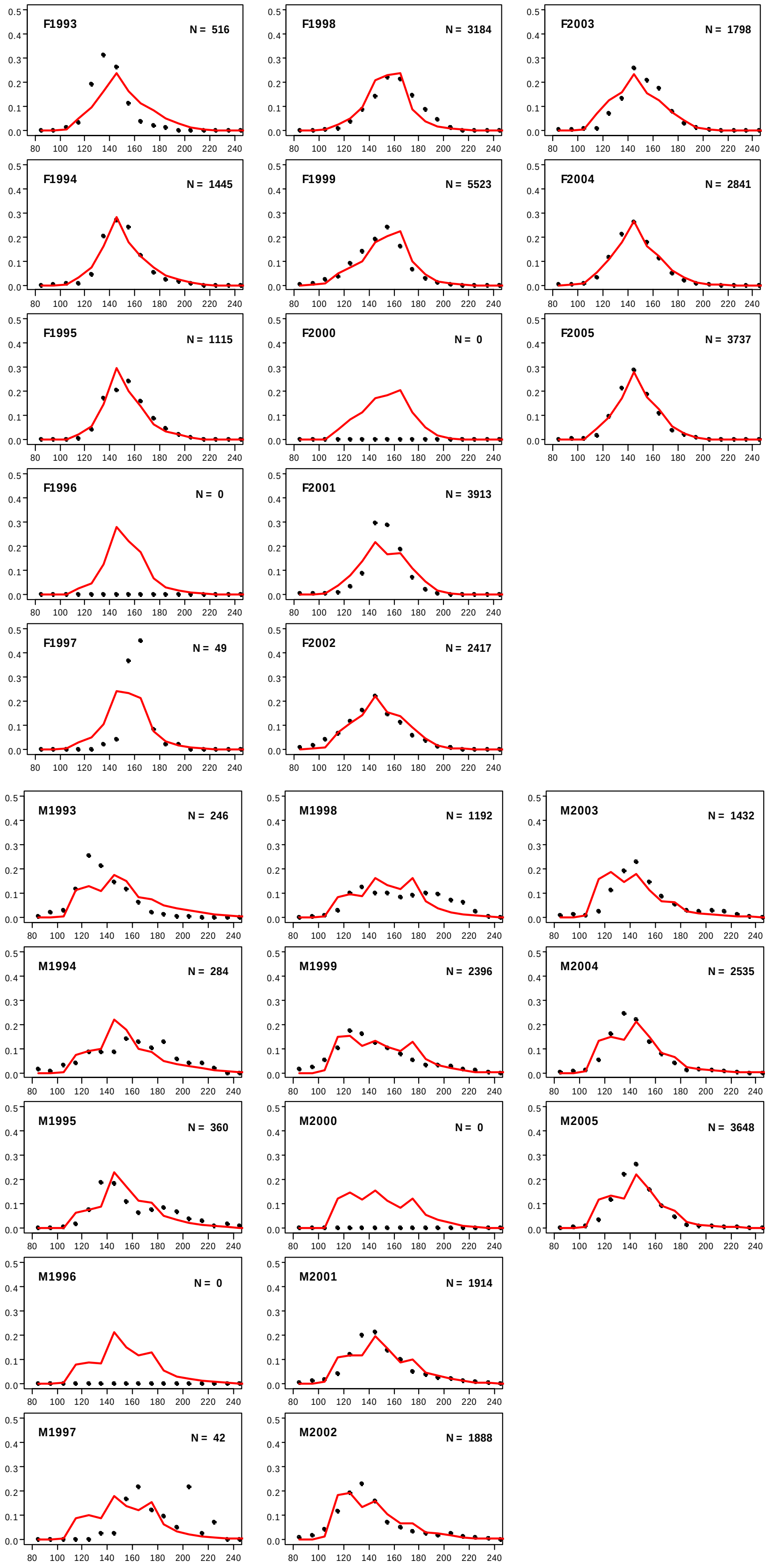

**Figure 18.** Observed (points) and predicted (lines) length frequencies of the commercial catches between 1993/94 (F1993 and M1993) and 2005/06 (F2005 and M2005) for female and male giant crab with the observed sample sizes *N*.

The bootstrap procedure permitted the generation of 90% percentile confidence intervals around the estimates of harvest rate and exploitable biomass providing an indication of the precision with which the model operates (Figure 19).

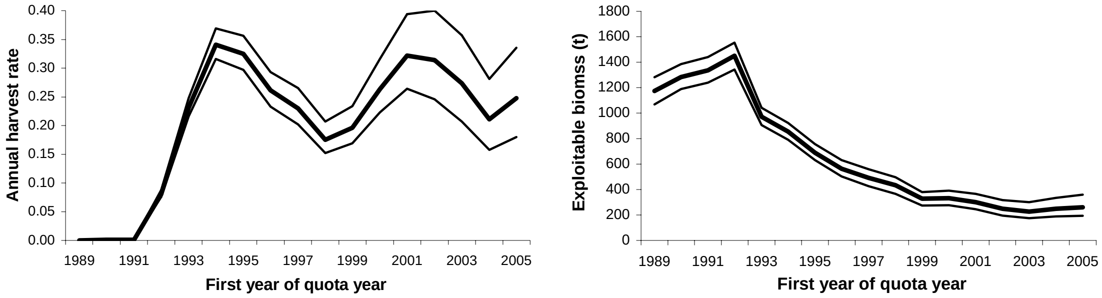

**Figure 19.** The predicted annual harvest rate and exploitable biomass at the start of each quota year (first year of the quota year given). The heavy lines indicate the median values while the lighter outer lines are the 90% bootstrap percentile confidence intervals around each variable.

### 3.3.5 Model Projections

In all cases, the projections had very wide confidence intervals around the predicted future values (Figure 20 and Figure 21). Recruitment variation cannot be fitted well to the last two years of the commercial catch rate data because of the low selectivity of the traps for newly recruited crabs entering the smallest size classes (80 mm). Hence the recruitment variation required for the projections begins in 2004/05 rather than 2006/07. This means that by the first year of the projection the confidence intervals around the model outputs of total biomass and egg production are already quite wide. The generally broad bounds of the confidence intervals illustrate that these projections are highly uncertain.

The projected outcomes of the TACC scenarios with 51.8 t and 62.1 t are very similar (Figure 20). The higher catch results in higher harvest rates and slightly lower (yet still increasing) catch rates, while total and exploitable biomass are almost identical. Both scenarios indicate an over 80% chance of stock rebuilding, however this is likely to occur only slowly.

A higher TACC of 82.8 t and the old TACC of 103.5 t on the other hand indicate that exploitable biomass and catch rates are more likely to drop, in the latter case with an over 50% chance (Figure 21). With the highest TACC, the upper limit on the confidence bound of the predicted harvest rate is also only determined by a limit imposed by the model to avoid unrealistic answers after just a few years, *e.g.* greater than 100% of available legal-size biomass being taken in the fishery. Similarly, the exploitable biomass reaches a lower threshold below which there would not have been enough available biomass to be consistent with the history of the fishery.

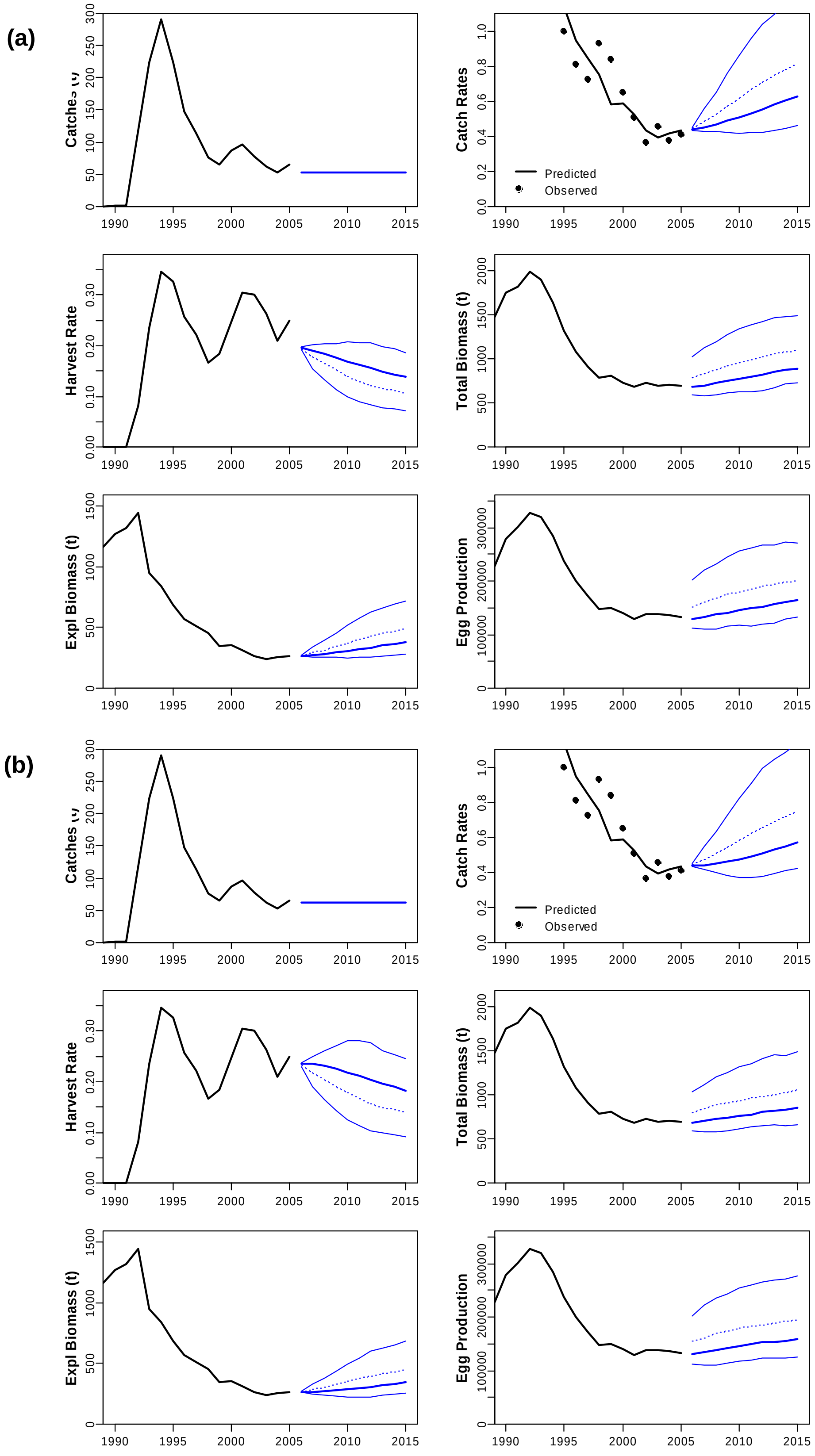

**Figure 20.** Model outputs for a 10-year projected TACC of (a) 51.8 tonnes and (b) of 62.1 tonnes, the current TACC, derived from 1000 projections. In the projections, 80% of all simulations were above (or for harvest rate below) the bold line ($P_{80\%}$), while 50% of all simulations were above the dotted line (median). The outer solid lines relate to the 90% percentile confidence intervals.

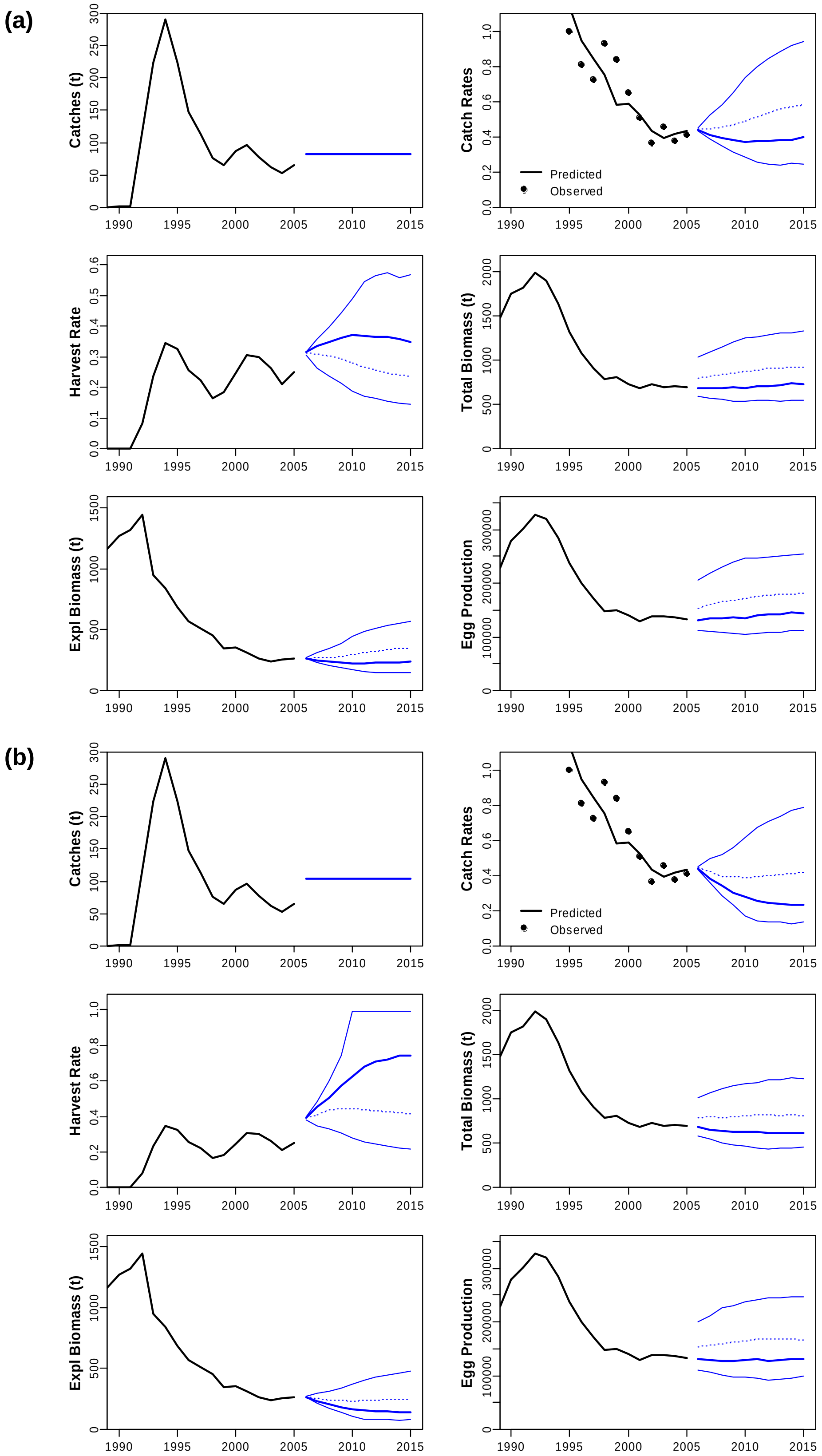

**Figure 21.** Model outputs for a 10-year projected TACC of (a) 82.8 tonnes and (b) 103.5 tonnes derived from 1000 projections. In the projections, 80% of all simulations were above (or for harvest rate below) the bold line ($P_{80\%}$), while 50% of all simulations were above the dotted line (median). The outer solid lines relate to the 90% percentile confidence intervals.

### 3.3.6 Conclusions from population modelling

The process of fishing down the Tasmanian giant crab fishery appears to have ended with exploitable biomass now stabilising at around 20% of the virgin state.

The model predicts that the current TACC of 62.1 t should lead to a slow increase in stock over the next five to 10 years unless factors not included here become involved (*e.g.* trawl interactions become significant). The risk of stock decline increases with TACC. With a TACC of 103.5 t there is only a 50% chance that there will be any stock rebuilding over the next 10 years. Equivalently, there would be a 50% chance of a stock decline.

Reproductive capacity of the stock appears less sensitive to changes in TACC with an estimated 80% probability of egg production remaining stable even under the highest TACC scenario of 103.5 t. This is a function of the size limit, which enables females less than 150 mm CL to contribute to egg production regardless of the harvest rate.

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# 5. Appendix 1: Length-based stock assessment model

## 5.1 Length-Based Modelling

See FRDC report 2002/238 on the ‘Development of the tools for long-term management of the giant crab resource: Data collection methodology, stock assessment and harvest strategy evaluation’ for further details.

As with many other invertebrate species, giant crabs (*Pseudocarcinus gigas*) cannot be aged with any degree of ease or accuracy. An alternative way of describing the population dynamics of such a species is to use a size-based model (*e.g.* Punt and Kennedy 1997). The principle behind such models is that a vector of numbers at size $\mathbf{N_l}$ is projected through time by multiplying it by a square matrix representing the probabilities of growing from one size class into a subsequent set of size classes over the period of time represented by the matrix **G**. In addition, survivorship following natural and size-selective fishing mortality $\mathbf{S_l}$ occurs along with new recruitment **R** as follows:

$$\mathbf{N_{l,t+1} = S_{l,t} G N_{l,t} + R} \tag{5.1}$$

The time step and size-class selected in such models tends to be fixed at some convenient period and width over which data is available. The model here used 5 mm size-classes between 80-250 mm carapace length. Problems could arise if the maximum growth that occurs for a given size-class within a single time-step is less than the width of the size-class. If that occurs then the animals could become mathematically trapped with no hope of ever growing out of this effectively terminal size-class. In effect, this final size-class would be the equivalent of a plus group and this would only be a bad thing if this imposed excessive distortion on the description of numbers at size.

If the time-step that the growth transition matrix represents is markedly different from the biological properties of the species concerned, a proportion of animals may not moult in the available time. This lack of growth can be accommodated for small difference between the moulting interval and the time-step of the transition matrix by including the probability of not growing out of the size-class into the transition probabilities. However, this option obscures the real dynamics of the time-lags in moulting if the moulting interval was very long relative to the time-step of the transition matrix.

Such moulting intervals reach extremes in the Tasmanian giant crab, in which large animals can go many years between moults (Gardner *et al.* 2002, McGarvey *et al.* 2002). One way of attempting to capture the dynamics involved with such delays in moulting is to model the probability of moulting in a particular year in an explicit way. Then the probability of moulting depends upon both the size of the animals, the sex of the animals and the time since the animals last moulted. The moulting model is used to determine in each year how many within each size-class were expected to moult. A growth transition matrix with a time-step of one year is then applied to those animals expected to moult.

In the case of the Tasmanian giant crab, the intermoult intervals are modelled explicitly through a new matrix of the numbers of years spent in each size class before moulting. Thus, in each year instead of a single vector of numbers-at-size $\mathbf{N}_{\mathrm{m}}$ for each sex representing the total population across $m$ size-classes, the number-at-size for each sex are distributed within a matrix $\mathbf{N}_{\mathrm{m,y}}$ describing the maximum number of years $y$ for which the moulting dynamics are followed (Eq. (5.2)). Thus, with $m$ size classes following $y$ years of moulting history for each size class we end with a matrix of the following form to describe numbers-at-size:

$$
\begin{array}{ccccccccc}
\mathbf{N}_m & & & & \mathbf{N}_{m,y} & & & & \\
N_1 & & N_{1,1} & N_{1,2} & N_{1,3} & . & . & . & N_{1,y} \\
N_2 & & N_{2,1} & N_{2,2} & N_{2,3} & . & . & . & N_{2,y} \\
N_3 & & N_{3,1} & N_{3,2} & . & . & . & . & . \\
. & \Rightarrow & . & . & . & N_{4,4} & . & . & . \\
. & & . & . & . & . & . & . & . \\
. & & . & . & . & . & . & . & . \\
. & & . & . & . & . & . & . & . \\
. & & . & . & . & . & . & . & . \\
N_m & & N_{m,1} & . & . & . & . & . & N_{m,y}
\end{array}
\tag{5.2}
$$

This matrix is complemented by an equivalent order matrix describing the proportion in each size class in each year of the moulting history, that will moult in the given year $\mathbf{P}_{\mathrm{m,y}}$. In short, this means that instead of following the fate of a vector of numbers-at-size the process follows a matrix of numbers-at-size by years-to-moult.

### 5.1.1 Model Structure

With size-based models, the order in which the different drivers to the dynamics occur can have a significant influence on the outcomes (Haddon 2001, p. 219), so the sequence of matrix operations is important. The sequence of operations acting on the matrix of numbers-at-size for each sex to describe the population dynamics in each year can be formally described. The numbers-at-size $i$ by years-to-moult $j$ matrix for sex $k$ at time $t$ can be represented by $N_{i,j}^{k,t}$ or in matrix notation $\mathbf{N}^{\mathbf{k,t}}$. The various stages in the algorithm will be represented by incrementing the time superscript $t$ by the stage of the operation (*a to m*; stage $n$ is the final step and is represented as $t$+1; stage names $i$, $j$, and $k$, are omitted to avoid confusion with subscripts in the equations). The dynamics can be represented by nine steps which follow a branching pathway (Figure 22):

a. Multiply the matrix of numbers-at-size (by years-to-moult) by the survivorship arising from applying half the background natural mortality ($M$/2):

$$N_{i,j}^{k,t+a} = N_{i,j}^{k,t} e^{-M/2} \tag{5.3}$$

b. Multiply the numbers-at-size by years-to-moult matrix by the moulting matrix for each sex $k$ $\mathbf{P^k}$ on a cell by cell basis, to identify $\Gamma$, those fish in each size-class $i$ and each year-to-moult $j$ that are due to moult:

$$\Gamma_{i,j}^{k,t+b} = P_{i,j}^{k} \times N_{i,j}^{k,t+a} \qquad \text{for each } i \text{ and } j \tag{5.4}$$

c. Remove the numbers to moult from each size-class

$$N_{i,j}^{k,t+c} = N_{i,j}^{k,t+a} - \Gamma_{i,j}^{k,t+b} \tag{5.5}$$

d. Project the remainder forward one year along the years-to-moult axis. Setting the maximum number of years used to track the time till moulting as $y_{\max}$. This action empties the first column of the matrix. $Y_{\max}$ acts as a plus group:

$$\begin{aligned} N_{i,y_{\max}}^{k,t+d} &= N_{i,y_{\max}}^{k,t+c} + N_{i,y_{\max}-1}^{k,t+c} & j = y_{\max} - 1 \\ N_{i,j+1}^{k,t+d} &= N_{i,j}^{k,t+c} & 1 \le j \le y_{\max} - 2 \end{aligned} \tag{5.6}$$

e. Generate a vector of numbers-at-size that will moult by summing the numbers to moult from each of the years-to-moult columns of $\Gamma$:

$$n_i^k = \sum_{j=1}^{y_{\max}} \Gamma_{i,j}^{k,t+b} \qquad \text{For each } i \tag{5.7}$$

f. Fill the first column of the number-at-size matrix by multiplying the vector of crabs due to moult $\mathbf{n^k}$, by the respective growth transition matrix for each sex $\mathbf{G^k}$ which includes survivorship from moulting mortality. This action refills the first column of the numbers matrix. The effect of moulting mortality, containing in $\mathbf{G^k}$ implies that the sum of $\mathbf{n^k}$ is greater than the sum of the first column of the numbers matrix ( $\sum N_{i,1}^{k,t+f}$ ):

$$N_{i,1}^{k,t+f} = \mathbf{G^k n^k} \tag{5.8}$$

g. Using $L_{\max}$ as the maximum size-class $W_i$ as the vector of weight at size-class $i$, and $V_i$ as the selectivity of size-class $i$, calculate the exploitable biomass for both sexes ($k$ = $M$ and $F$) and all size-classes:

$$T_i^k = \sum_{j=1}^{y_{\max}} N_{i,j}^{k,t+f} \qquad \text{For each } i \tag{5.9}$$

$$B_E^t = \sum_{k=M}^{F} \sum_{i=1}^{L_{\max}} T_i^k W_i^k V_i^k \tag{5.10}$$

h. Calculate the harvest rate, $H^t$ (conditioned on catch $C^t$) and then multiply $H^t$ by the selectivity for each size-class to spread the harvest rate over all size-classes. Use this to calculate the predicted catch by numbers $X_i^{k,t}$, including weight at size to determine the predicted catch as biomass:

$$H^t = \frac{C^t}{B_E^t} \qquad \mathrm{X}_i^{k,t} = T_i^k V_i^k H^t \tag{5.11}$$

$$\hat{C}^t = \sum_{k=M}^{F} \sum_{i=i}^{L_{\max}} X_i^{k,t} W_i^k \tag{5.12}$$

l. Remove the numbers caught at size from the numbers matrix by multiplying by the survivorship modified by the selectivity curve:

$$N_{i,j}^{k,t+l} = N_{i,j}^{k,t+f}\left(1 - V_i^k H^t\right) \tag{5.13}$$

m. Distribute the recruitment across the first six size classes:

$$N_{i,j}^{k,t+m} = N_{i,j}^{k,t+k} + R_i^t \qquad \text{for i = 1..6} \tag{5.14}$$

n. Remove the final half of natural mortality:

$$N_{i,j}^{k,t+1} = N_{i,j}^{k,t+l} e^{-M/2} \tag{5.15}$$

### 5.1.2 Recruitment

Instead of estimating an annual recruitment for each year of the fishery, a (geometric) mean recruitment level $\bar{\mathbf{R}}$ is assumed for each region multiplied by a log-normal recruitment residuals $\varepsilon_t$ around this mean. This mean recruitment plus a recruitment residual for each year constitute the main parameters of the model. The sex ratio of the annual recruitment is assumed to be 1:1, and recruitment is assumed to occur into the first six size-classes only:

$$R_{1..6}^{k,t} = \bar{R} e^{\varepsilon_t} / 12.0 \tag{5.16}$$

If the model were allowed to fit to the recruitment residuals in an unconstrained fashion there is the possibility of extremely good fits but unrealistically variable recruitment levels. It is usual to set a coefficient of variation for the recruitment residuals ($\sigma_R$) and develop a penalty function designed to constrain recruitment variation that is added to the total log-likelihood:

$$Penalty = \frac{\sum_{k=1}^{years} \left(\varepsilon^k\right)^2}{2\sigma_R^2} \tag{5.17}$$

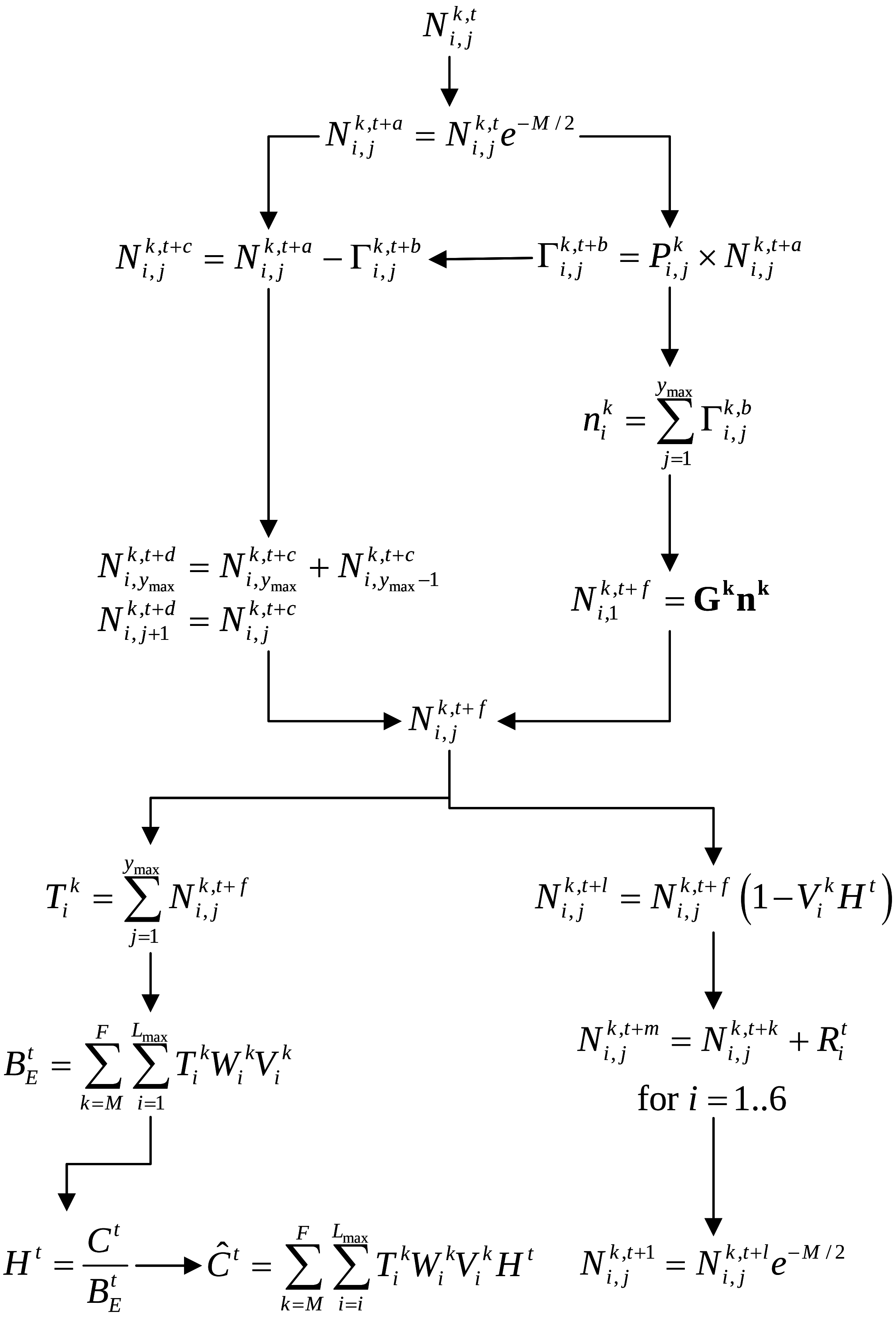

**Figure 22.** Schematic flow chart of the operations included in the algorithm for one time step of the Tasmanian giant crab model. All symbols are as described in Equations (5.3) to (5.15).

### 5.1.3 Catches

The harvest rate $H^t$, the proportion of available or exploitable biomass taken, is calculated by assuming that the total commercial catch including bycatch is taken instantaneously in the middle of the season, after half the natural mortality and growth of those animals that are to moult, has occurred (Eq. (5.11)).

### 5.1.4 Catchability

Catchability is likely to vary across the seasons and may affect the sex ratio. However, on a yearly time scale seasonal variations should average out across years. A closed form or analytic estimation method is used to estimate the catchability. This involves comparing the observed catch rates with the exploitable biomass that gave rise to the catch rates (Haddon 2001), as described below in the section detailing with the likelihood component relating to catch rates.

### 5.1.5 Growth Transition Matrix

The growth transition matrix is a square matrix of length equal to the number of size classes, in which only the lower diagonal is populated. The upper diagonal is populated with zeros because negative growth is not assumed to occur. The expected mean growth increment for an animal of length $L_i^s$ (the midpoint of size-class *i*) over a single time period was obtained from the linear regressions of moult increment versus premoult carapace length for both single moults and double moults:

$$\begin{array}{ll} \bar{\Delta}_i^1 = a + bL_i^s + \varepsilon & \text{one moult} \\ \bar{\Delta}_i^2 = 2\left(a + bL_i^s\right) + b(a + bL_i^s) + \varepsilon & \text{two moults} \end{array} \tag{5.18}$$

The expected mean length $\bar{L}_i^s$ of an animal of sex *s* and of size-class *i* (identified by the mid-class-length $L_i^s$) one moult later is:

$$\bar{L}_i^s = L_i^s + \bar{\Delta}_i \tag{5.19}$$

Equation (5.19) is used to generate the growth transition matrix. Detailed descriptions of the intermoult dynamics, and the moulting mortality is provided in the FRDC report.

### 5.1.6 Size at Maturity

The maturity-at-size $P_{\mathrm{i}}$ for females is described by a standard logistic curve relating the proportion of females mature to their size-class $L_{\mathrm{i}}$:

$$P_i = \frac{1}{1+e^{-(a+bL_i)}} \tag{5.20}$$

### 5.1.7 Fecundity at Size

A power relationship (Gardner 1997) is assumed to hold between fecundity $O_i$ and the size-class of female crabs:

$$O_i = cL_i^d \tag{5.21}$$

where $c$ and $d$ are the parameters of the power relationship. Extrusion of eggs tends to occur in May and extends through November into December. This has implications for the fishery because it is illegal to land ovigerous females and the closed season for females only extends to the end of October. All females caught are discarded between May and October, and ovigerous females are discarded at all other times (in practice in November and December). Currently it is assumed that there is no mortality associated with discarding, but this may need to be implemented to investigate the sensitivity of the dynamics to this potential issue. One way of including this discarding of ovigerous females is to alter the selectivity for females to reduce the total retained.

### 5.1.8 Selectivity

Selectivity of the gear is assumed to match a standard logistic curve. An alternative might be a logistic with a reducing tail for the very large size classes. While no information is available to differentiate between these, both trawl caught specimens and visual observations using benthic cameras do not indicate an abundance of very large crabs, so the second option is less likely. Selectivity is assumed to be described by a logistic curve for both sexes but with independent parameters. A simple logistic is fitted with two parameters, $\mathrm{L50}^{\mathrm{k}}$ and $\mathrm{L95}^{\mathrm{k}}$, with the $k$ superscript denoting the separate sexes, representing the carapace lengths at which 50% and 95% are selected:

$$\begin{aligned} V_i^{k,t} &= \frac{\pi}{1+e^{-\mathrm{Ln}(19)\left(\frac{i-L50^k}{L95^s-L50^k}\right)}} && LMinL < i < LMaxL \\ V_i^{k,t} &= 0 && i < LMinL, i > LMaxL \end{aligned} \tag{5.22}$$

where $\mathrm{L95}^{\mathrm{k}} = \mathrm{L50}^{\mathrm{k}}$ x $\mathrm{Scale95}^{\mathrm{k}}$. To ensure that the L95 is greater than the L50 it is made up of the L50 term multiplied by a scaling parameter that is constrained to lie between 1.01 and 1.5.

Changes to selectivity following changes to the legal size limits are accounted for through the use of the *t* subscript and setting particular sizes to zero selectivity depending on the legal limits (Eq. (5.22)). The selectivity for females needs to be modified to account for the closed season for females (May 1 to October 31) and for the average proportion of ovigerous females during the open season. This is implemented by multiplying the selectivity for females by a constant $\pi$. This constant can be estimated by multiplying the proportional monthly catch by the monthly proportion of ovigerous females (or by one during the female closed season) to determine the proportion of the total catch of females that can be expected to be ovigerous. For males $\pi$ is set to 1.0.

Sub-legal and super-legal sized animals are returned to the sea, and currently the model assumes zero discard mortality. A discard mortality could be implemented by increasing the portions of the selectivity curve (Eq. (5.22)) below the legal minimum length and above the legal maximum length from zero to the predicted death rate from being discarded. Thus, if there is a 10% discard mortality then the selectivity values above and below the legal lengths are multiplied by 0.1. The summation of catch would still need to exclude animals from above and below the legal limits as would the estimation of exploitable biomass. This could be implemented by having two selectivity curves for each sex, one with discards and one without, such that the removal of discards from the numbers matrix would not contribute to the landed catch.

### 5.1.9 Natural Mortality

Natural mortality is modelled in two ways. The first is the background natural mortality rate across all size-classes each year. This is implemented as a survivorship ($e^{-M}$) with which the matrix of numbers-at-size by years-to-moult is multiplied. In an effort to model some of the within season dynamics, the background natural mortality is implemented by two applications of half the natural survivorship ($e^{-M/2}$), one before fishing mortality occurs and one after.

The second form of natural mortality was implemented as a natural mortality rate associated with moulting. This was modelled as a linear relationship between the instantaneous moulting mortality and size-class. When the linear instantaneous moulting mortality rate is converted to a survivorship it becomes a non-linear descending curve. The vector of survivorships were placed into the diagonal of a square matrix and used to multiply the growth transition matrix for each sex. In this way the moulting mortality was automatically coordinated with growth when it occurs.

### 5.1.10 Initial Conditions

For many years before the giant crab fishery developed, rock lobster fishers caught predominantly large males as minor bycatch. Very little of this was landed and the stock was essentially unfished until the target fishery developed. Without independent information with regard the state of the stock, it was assumed that the stock was in equilibrium with its mean recruitment level at the time the fishery began.

With a simple growth description that did not require the use of tracking the years-to-moult, the equilibrium numbers-at-size was generated in an analytical fashion. However, the added complexity of the years-to-moult matrix representation meant that the equilibrium conditions needed to be determined iteratively. In practice, the population was initiated by starting with an empty numbers-at-size by years-to-moult matrix (the numbers matrix) and distributing the total recruitment across the first six size-classes. The equilibrium state within the numbers matrix was attained after 200 passages through a routine for updating the stock dynamics in the absence of fishing. The stock dynamics routine involved applying half the natural mortality, identifying those animals that would grow and subtracting them from the numbers matrix. The numbers matrix was then incremented one year forward and the first column of the numbers matrix filled with the numbers-to-moult multiplied by the respective growth transition matrix. There was no fishing mortality so the dynamics moved immediately to removing the last half of natural mortality.

## 5.2 Likelihood Functions for Model Fitting

### 5.2.1 Catch Rate Data

Assuming catch rates are log-normally distributed leads to the following likelihood:

$$L_{CE} = \prod_{t} \frac{1}{I_t \sqrt{2\pi}\,\sigma_q} \exp\left( -\frac{\left(\mathrm{Ln} I_t - \mathrm{Ln}\left(qB_t^E\right)\right)^2}{2\sigma_q^2} \right) \qquad (5.23)$$

where $\sigma_q$ is the standard deviation of the residual errors around the expected catch rates, $I_t$ is the catch rate for year *t*, and $B_E^t$ is the exploitable biomass after half of natural mortality and growth have occurred. This equation can be greatly simplified as a negative log-likelihood (minimizing this leads to the maximum likelihood estimate):

$$-LL_{CE} = -\frac{n}{2}\left(Ln(2\pi) = 2Ln(\hat{\sigma}) + 1\right) - \sum_{t=1}^{Years} Ln\left(I_t\right) \qquad (5.24)$$

For further simplicity the final summation term of Ln(*I*) is a constant and can be omitted without affecting the outcome. The value of $\hat{\sigma}$ can be obtained using the maximum likelihood estimate; note the use of *n* and not *n*-1 in the denominator:

$$\hat{\sigma} = \sqrt{\frac{\sum_{t=1}^{Years}\left(Ln\left(I_t\right) - Ln\left(\hat{I}_t\right)\right)^2}{n}} \qquad (5.25)$$

In addition, the maximum likelihood estimate of *q*, which optimises Eq. (5.24) can be determined analytically as:

$$\hat{q} = \exp\left( \frac{\sum_{t} Ln\left(I_t / B_t^E\right)}{n} \right) \qquad (5.26)$$

where *n* is the number of years for which catch rates are available (Haddon 2001).

### 5.2.2 Length Frequency Data

It is assumed that the length-frequency data available will be fitted using a multinomial likelihood (Quinn and Deriso 1999, Haddon 2001). Thus:

$$L_{LF} = n!\prod_{i=1}^{L_{\max}} \frac{p_i^{n_i}}{n_i!} \tag{5.27}$$

where

$$n = \sum_{i=1}^{L_{\max}} n_i \tag{5.28}$$

and $p_i$ are the expected probabilities for each size class $i$. When this is converted to a negative log-likelihood we obtain:

$$-LL_{LF} = -\sum_{j=1}^{n} Ln(j) - \sum_{i=1}^{L_{Max}} \left[ n_i Ln(p_i) - \sum_{j=1}^{n_i} Ln(j) \right] \tag{5.29}$$

The first and last terms are merely the logarithmic form of calculating the factorial terms. For any particular problem these terms are constant and are usually ignored in the calculation of the negative log-likelihood. For added stability the number of observations in each size-class $n_i$ can be converted to proportion by dividing by the sum of all the observations (Quinn and Deriso 1999). We are left with:

$$-LL_{LF} = -\sum_{i=1}^{L_{Max}} \frac{n_i}{n} Ln(p_i) \tag{5.30}$$

A constant second term that depends only on the observed proportions is added that causes the log-likelihood for the observation to approach zero from below as the model fit improves:

$$-LL_{LF} = -\sqrt{N} \sum_{i=1}^{L_{Max}} \left( \frac{n_i}{n} Ln(p_i) - \frac{n_i}{n} Ln\left( \frac{n_i}{n} \right) \right) \tag{5.31}$$

and the whole log-likelihood is weighted by a measure of sample size. Because samples which are usually taken in clusters can have a reduced within-cluster variance relative to samples where fish are taken individually, the square root rather than the real the sample size was used as ‘effective’ sample size. When Eq. (5.31) is minimized the match between the observed length frequencies and those predicted by the model is optimised.

### 5.2.3 Total Likelihood

The model is fitted by combining the various sources of likelihood and the penalty term from the recruitment residuals (Eqs. (5.17), (5.24), and (5.31)). Each of the likelihood terms was weighed with the inverse proportion to their respective variation (*i.e.* less weight to the more variable). These weights can also be used to explore the relative contribution of each source of likelihood to the final solution:

$$-LL = -LLCE * WtCE + -LLLF * WtLF + \text{Penalty} \tag{5.32}$$

# 6. Appendix 2: Standardisation of catch rates for Tasmanian giant crab

## 6.1 Introduction

As in most fisheries, catch rates obtained from catch returns by commercial fishers can be assumed to constitute an index of relative stock abundance through time. However, many other factors can influence catch rates besides the relative stock abundance. In the case of giant crabs, targeting crabs, location, season and depth of fishing, and skipper are all intuitively likely to be important factors influencing the observed catch rates. Standardising catch rates using generalized linear models (GLM) generally reduces the impact of these obscuring effects (Kimura 1981, 1988). However, while standardisation is preferred to the geometric mean of raw catch rates, there remains no guarantee that a relation exists between the standardised catch rates and stock size, as other factors may have effects on changes in biomass that are unaccounted for by the statistical model. At least, the standardised catch rates should provide an improvement over the raw catch rates.

The giant crab fishery operates on both the east and west coast of Tasmania. Catches are mainly taken by two groups of around ten operators, and there is a small amount of bycatch taken by rock lobster fishers on the west coast (Gardner 1998). In the latest years, around 90% of the total catch on the west coast was taken by the top ten fishers, while there have been 10 or fewer fishers since 2001/02 on the east coast.

All of the targeted fishing for giant crab in Tasmanian waters takes place on the edge of the continental shelf. On the west coast there are catch modes in the 180m and 280m depth categories, while the only major modal depth on the east coast was the 280m depth category (Figure 23).

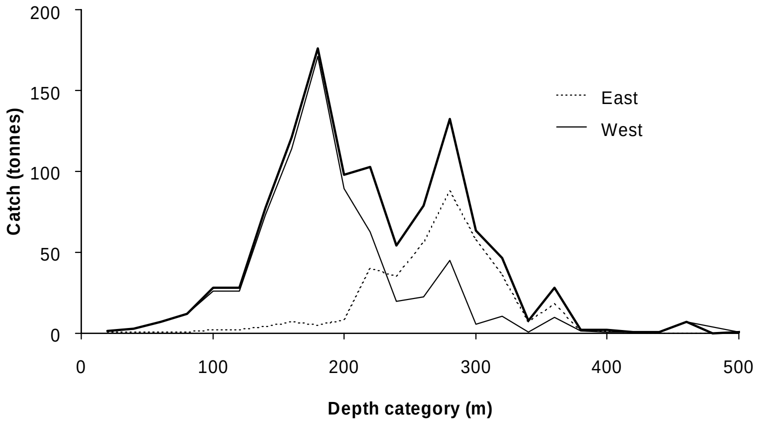

**Figure 23. D**istribution of total catches by 20m depth category for the west and east coast across the history of the fishery.

## 6.2 Methods

Catch rates or catch per unit effort (CPUE) were estimated as kilograms per pot days for each record in the database as:

$$\text{CPUE} = \frac{\text{Weight of catch (kg)}}{\text{Number of traps} \times \text{Soak time}} \tag{5.33}$$

where pot days are defined as the number of traps multiplied with number of days the traps are in the water before being hauled (soak time). Soak time capped at 7 days, based on the belief that soak times greater than 7 days do not lead to increases in catch, resulted in reduced normality of the (log-transformed) data and was not used.

The period under analysis included two different management arrangements with fisheries data being recorded in different logbooks. Before July 1998, fishing was restricted to fishers with commonwealth permits issued by AFMA with effort limited by gear restrictions. A total of 106 permits were issued to holders of Tasmanian rock lobster endorsements (Gardner 1998), and catch effort data was recorded in the general fish logbook. Up until 1994, the general fish logbook did not contain records of effort, and hence data prior to the 1995/96 quota year cannot be included in this analysis. The new general fish logbook introduced in January 1995 included the date of fishing and data on the weight of the catch, number of traps used, soak time, location by 30 minute block, and average depth of fishing. In November 1999, a new management plan for giant crab was introduced by the State Government that set the total allowable commercial catch (TACC) to be 103.5 tonnes and the creation of a new type of fishing licence (giant crab). A new logbook for giant crab was introduced at the same time and required additional information. The new Integrated Catch Effort (ICE) logbook extended the old logbook by data on the latitude and longitude of fishing and whether a fisher was targeting giant crab.

Since information on targeting giant crab has been included in the logbook returns only in the most recent years, a number of criteria were developed for data selection in order to restrict the analysis to those records most likely to have been targeted at giant crabs. The data selection was based on vessel rather than skipper because quota licences are attached to vessels. Only vessels that had been in the fishery for a minimum of 2 years with a median catch of at least 1000 kg per year during that period were considered for the analysis. Any remaining vessels were removed as they were believed to contribute primarily statistical noise to the assessment rather than useful information. By applying these criteria, 89.6% of the total catch by weight and 79.7% by number of records are accounted for in the analysis (Table 4).

Data from the general fish logbook and the ICE logbook databases were extracted and combined into a single Access database for use in the following analyses. Data from previous years had been further checked and corrected for errors.

**Table 4.** The overall number of records (All records) and the numbers used in the standardisation (Selection) for vessels in the fishery for at minimum of 2 year with a median catch of at least 1000 kg for each quota year. East and west are defined as either side of longitude 147ºE.

| **Quota year** | **All records** | **Selection** | | | |
|---|---|---|---|---|---|
| | | **East** | **West** | **All** | **Proportion** |
| 1995/96 | 1387 | 292 | 634 | 926 | 66.8% |
| 1996/97 | 1377 | 147 | 729 | 876 | 63.6% |
| 1997/98 | 1108 | 234 | 594 | 828 | 74.7% |
| 1998/99 | 509 | 189 | 199 | 388 | 76.2% |
| 1999/00 | 1091 | 567 | 330 | 897 | 82.2% |
| 2000/01 | 1526 | 546 | 696 | 1242 | 81.4% |
| 2001/02 | 1434 | 373 | 869 | 1242 | 86.6% |
| 2002/03 | 1322 | 395 | 767 | 1162 | 87.9% |
| 2003/04 | 1051 | 359 | 582 | 941 | 89.5% |
| 2004/05 | 856 | 300 | 484 | 784 | 91.6% |
| 2005/06 | 735 | 208 | 417 | 625 | 85.0% |
| Total | 12396 | 3610 | 6301 | 9911 | 80.0% |

The raw catch rate data were not normally distributed, thus, the data was first natural log-transformed to improved normality before the standardisation (Figure 24 and Figure 25). The procedure ‘lm’ for fitting linear models (equivalent to a generalised linear model using a normal distribution family with an identity link) inside the statistical package R was used for the statistical analyses. The models were fitted to different combinations of various factors for which information were available, *viz*. skipper, 20m depth category, month fished, 30º fishing block, and number of traps. The use of fishing block captured all information that was implicit in the East/West distinction.

All models were fitted using a forward approach by stepwise addition of each factor starting with the annual time-step. The initial factor that fitted the data the best would be added to the model first, then the next best factor would be added and so on until additional factors or interactions no longer improved the model fits. Some interaction terms between various factors were also considered, but these were limited to combinations for which sensible interpretations could be ascribed.

The optimal model was chosen based on minimization of Akaike’s Information Criterion (AIC; Burnham and Anderson 2002). Generally, the more independent parameters that are added the greater the amount of variability is explained. The AIC can be viewed as an attempt to balance the maximum amount of variability in the data accounted for with the least number of parameters used to describe the data (although this heuristic interpretation does not fully do justice to the underlying theory of the AIC).

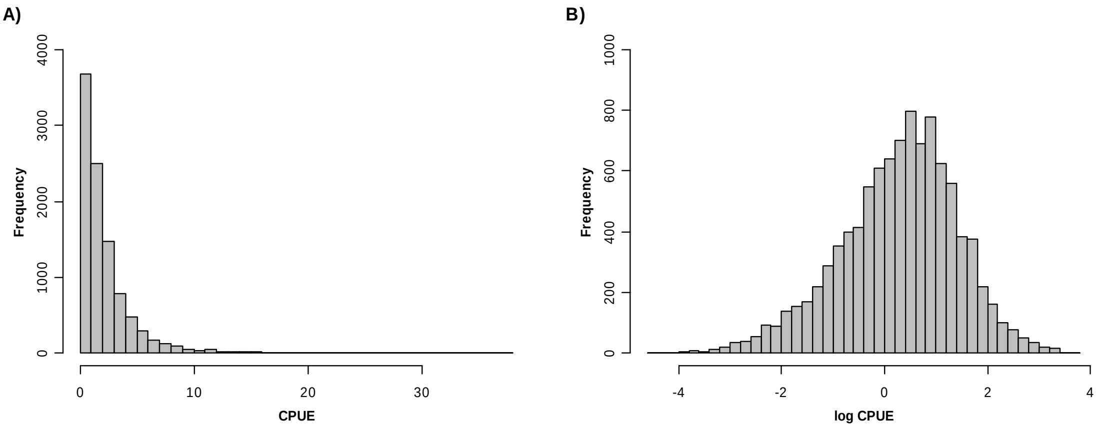

**Figure 24.** Distribution of (A) raw catch rate data and (B) natural log-transformed catch rate data.

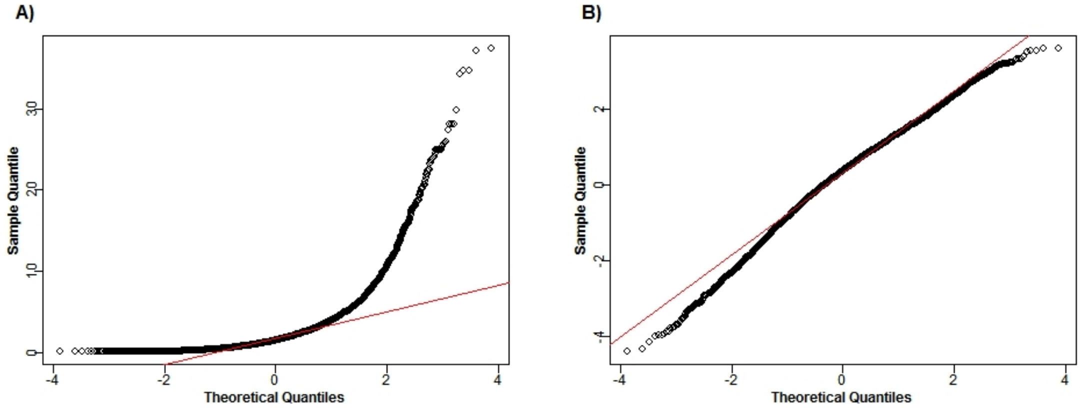

**Figure 25.** Quantile-Quantile plot of (A) raw catch rate data and (B) natural log-transformed catch rate data.

For large data sets and models with normally distributed errors and constant variance, the AIC can be computed from least squares regression as (Burnham and Anderson 2002, p. 63):

$$\text{AIC} = N * \text{Ln}\left(\frac{\text{SSE}}{N}\right) + 2K \tag{5.34}$$

where SSE is the sum of the squared residuals, $N$ is the total number of observations, and K is the number of parameters. The models with the lowest AIC or within 2 of the lowest AIC provide the optimum fit of all tested models.

In addition, the adjusted $R_A^2$ gives a better estimate of total variability described by the statistical model than the simple $R^2$ (Neter *et al.* 1996) with $n$-$K$ degrees of freedom:

$$R^2 = 1 - \frac{SSE}{SSTO}, \quad R_A^2 = 1 - \frac{\frac{SSE}{n-K}}{\frac{SSTO}{n-1}} = 1 - \left(\frac{n-1}{n-K}\right)\left(\frac{SSE}{SSTO}\right) \tag{5.35}$$

where SSTO is the total sum of squares calculated as the SSE plus the variation due to the statistical model with *n*-1 degrees of freedom. “This adjusted coefficient of multiple determination may actually become smaller when another *X* variable is introduced into the model; because any increase in SSE may be more than offset by the loss of a degree of freedom in the denominator *n-K*” (Neter *et al.* 1996, p. 231).

When the optimal model had been identified, residual plots and QQ-plots were examined to confirm that the data still conformed to the statistical assumptions under the model.

## 6.3 Results

Given the factors available, eleven different statistical models were considered (Table 5). The geometric mean by itself (Model 1) accounted for only 9.0% of the variability (Table 6). The skipper conducting the fishing had greater influences than the quota year. The depth at which the fishing occurred and the month of fishing were also important. The interaction terms substantially improved the fits, with Model 10 providing the optimum fit of all the models tested with just below 60% of the variation described. The diagnostics of Model 10 indicated that the fit to the data was reasonable (Figure 26). The fit of Model 11 was second best and with only two-way interaction terms easier to interpret than Model 10 that contained a three-way interaction term. Both models indicated that the interactions between skipper, month and block were very influential, with variable seasonal locations between individual fishers.

**Table 5.** Descriptions of the statistical models compared for giant crab around Tasmania at a time step of quota years. LnCE is the natural log of catch (kg) per pot days, Qyear is quota year, DepCat is the 20m depth category, Block is the 30º statistical reporting area, and Traps is the number of pots used. Model 1 is equivalent to the geometric mean of catch rates and acts as a Base Case against which the other models are compared.

| | |
|---|---|
| Model 1 | LnCE = Const + Qyear |
| Model 2 | LnCE = Const + Qyear + Skipper |
| Model 3 | LnCE = Const + Qyear + Skipper + DepCat |
| Model 4 | LnCE = Const + Qyear + Skipper + DepCat + Month |
| Model 5 | LnCE = Const + Qyear + Skipper + DepCat + Month + Block |
| Model 6 | LnCE = Const + Qyear + Skipper + DepCat + Month + Block + Traps |
| Model 7 | LnCE = Const + Qyear + Skipper + DepCat + Month + Block + Traps + Skipper*Month |
| Model 8 | LnCE = Const + Qyear + Skipper + DepCat + Month + Block + Traps + Skipper*Block |
| Model 9 | LnCE = Const + Qyear + Skipper + DepCat + Month + Block + Traps + Month*Block |
| Model 10 | LnCE = Const + Qyear + Skipper + DepCat + Month + Block + Traps + Skipper*Month*Block |
| Model 11 | LnCE = Const + Qyear + Skipper + DepCat + Month + Block + Traps + Skipper*Month + Month*Block |

**Table 6.** Statistical results from the standardisation of Tasmania giant crab data. Models are defined in Table 5. *N* is the number of data records, # Params is the number of parameters (*K*), df Params is the degrees of freedom for the statistical model, df Resids is the residual degrees of freedom (*N*-*K*), Model SS is the variation described by the model, Resid SS is the sum of squared residual errors, AIC is Akaike's Information Criterion, Var% is the raw $R^2$ value, Adj$R^2$ is the adjusted $R^2$, and Δ Adj$R^2$ are the improvements of each model's Adjust$R^2$ compared to the previous model (the values for Models 7 to 11 are relative to Model 6). Model 10 provided the optimum fit (in bold). The vertical line separates simple models (Models 1-6) from those that include interaction terms (Models 7-11).

| **Model** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *N* | 9910 | 9910 | 9910 | 9910 | 9910 | 9910 | 9910 | 9910 | 9910 | 9910 | 9910 |
| # Params | 11 | 58 | 82 | 93 | 150 | 151 | 406 | 408 | 383 | 974 | 617 |
| df Resid | 9899 | 9852 | 9828 | 9817 | 9760 | 9759 | 9504 | 9502 | 9527 | 8936 | 9293 |
| df Params | 10 | 57 | 81 | 92 | 149 | 150 | 405 | 407 | 382 | 973 | 616 |
| Model SS | 1178 | 3535 | 4522 | 5127 | 5548 | 5697 | 6770 | 6589 | 6733 | 8290 | 7453 |
| Resid SS | 11817 | 9460 | 8472 | 7868 | 7447 | 7298 | 6225 | 6405 | 6262 | 4705 | 5542 |
| AIC | 1766 | -345 | -1389 | -2100 | -2532 | -2730 | -3796 | -3509 | -3784 | **-5435** | -4526 |
| Var% | 0.091 | 0.272 | 0.348 | 0.395 | 0.427 | 0.438 | 0.521 | 0.507 | 0.518 | **0.638** | 0.574 |
| Adj$R^2$ | 0.090 | 0.268 | 0.343 | 0.389 | 0.418 | 0.430 | 0.501 | 0.486 | 0.499 | **0.599** | 0.545 |
| Δ Adj$R^2$ | 0.090 | 0.178 | 0.075 | 0.046 | 0.029 | 0.012 | 0.071 | 0.056 | 0.069 | **0.169** | 0.116 |

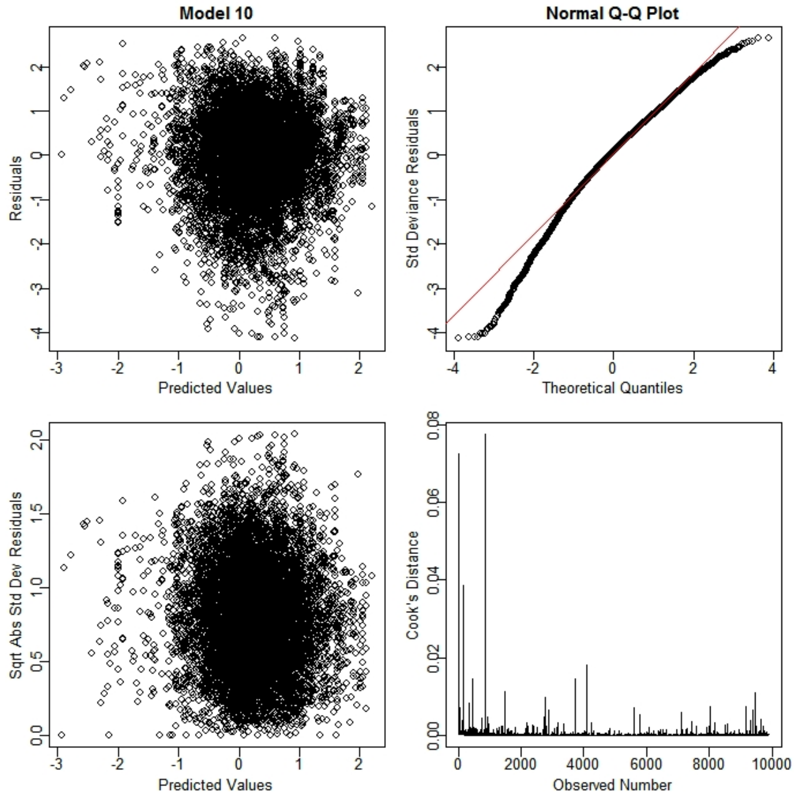

**Figure 26.** Diagnostics for the optimum Model 10 with a plot of residuals against fitted values (top left), a normal Quantile-Quantile (Q-Q) plot (top right), a Scale-Location plot of the square root of the absolute residuals against fitted values (bottom left), and a plot of Cook's distances versus row labels (bottom right).

With the exception of the year 1998/99, the standardised catch rates declined steadily from 1995/96 to 2002/03 and have since stabilised at around 40% of the levels in 1995/96 (Figure 27, Table 7). The overall effect of the standardisation was minor with the trends described by the simple geometric mean being fairly similar to the optimum model.

Most of the effect of the standardisation was brought about by the original selection of data to those vessels in the fishery for a minimum of two years with a median catch of at least 1000 kg per year during that time. If no data selection was made, the same Model 10 was optimal with a similar standardised time-series of catch rates (Figure 28). Only the geometric mean (Model 1) showed some major difference, while the other models were relatively close to those from the analysis with the selected data.

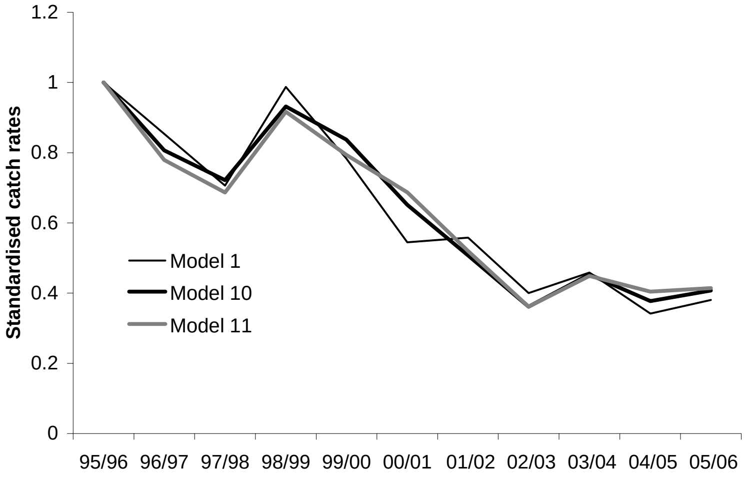

**Figure 27.** Standardised catch rates derived from Model 1 (geometric mean, thin black line), Model 10 (heavy black line) and Model 11 (heavy grey line) relative to catch rates in 1995/96, when data was restricted to vessels in the fishery for a minimum of2 years and with a median catch of at least 1000 kg.

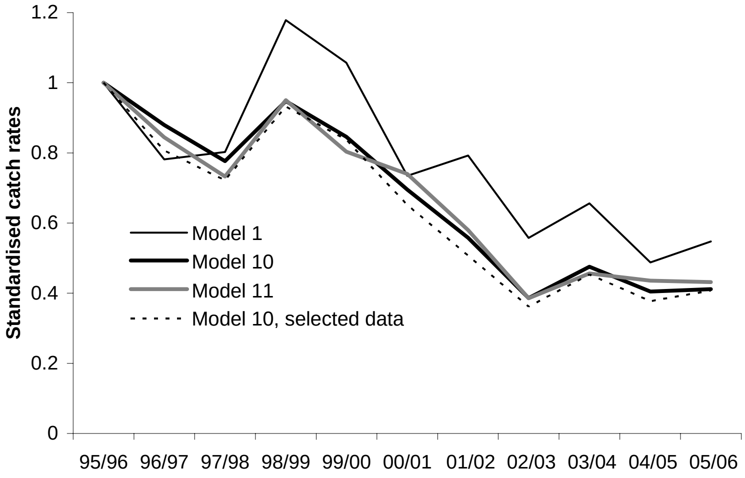

**Figure 28.** Standardised catch rates derived from Model 1 (geometric mean, thin black line), Model 10 (heavy black line) and Model 11 (heavy grey line) relative to catch rates in 1995/96, when all available data was used. The dotted line represents the optimum Model 10 (see Figure 27) when data was restricted.

**Table 7.** Predicted standardised catch rates for each model relative to the quota year 1995/96.

| Model | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1995/96 | 1. 00 | 1. 00 | 1. 00 | 1. 00 | 1. 00 | 1. 00 | 1. 00 | 1. 00 | 1. 00 | 1. 00 | 1. 00 |
| 1996/97 | 0.85 | 0.82 | 0.93 | 0.94 | 0.91 | 0.92 | 0.82 | 1.04 | 0.81 | 0.81 | 0.78 |
| 1997/98 | 0.71 | 0.68 | 0.74 | 0.75 | 0.77 | 0.76 | 0.68 | 0.82 | 0.74 | 0.72 | 0.69 |
| 1998/99 | 0.99 | 1.02 | 0.99 | 0.95 | 0.97 | 0.96 | 0.87 | 1.07 | 0.89 | 0.93 | 0.92 |
| 1999/00 | 0.78 | 1.20 | 1.00 | 0.93 | 0.92 | 0.74 | 0.74 | 0.85 | 0.69 | 0.84 | 0.79 |
| 2000/01 | 0.55 | 0.84 | 0.78 | 0.85 | 0.80 | 0.65 | 0.70 | 0.72 | 0.61 | 0.65 | 0.69 |
| 2001/02 | 0.56 | 0.77 | 0.68 | 0.77 | 0.70 | 0.56 | 0.58 | 0.61 | 0.48 | 0.51 | 0.52 |
| 2002/03 | 0.40 | 0.57 | 0.51 | 0.52 | 0.46 | 0.37 | 0.36 | 0.42 | 0.34 | 0.36 | 0.36 |
| 2003/04 | 0.46 | 0.73 | 0.65 | 0.59 | 0.56 | 0.43 | 0.44 | 0.48 | 0.39 | 0.45 | 0.45 |
| 2004/05 | 0.34 | 0.52 | 0.46 | 0.52 | 0.49 | 0.40 | 0.42 | 0.44 | 0.36 | 0.38 | 0.40 |
| 2005/06 | 0.38 | 0.66 | 0.60 | 0.63 | 0.57 | 0.49 | 0.44 | 0.53 | 0.40 | 0.41 | 0.41 |

## 6.4 Discussion

The data selection to restrict the records to those vessels in the fishery for a minimum of two years and with median catches of at least 1000 kg per year had only a minor effect on the outcome of the catch rate standardisation. While the geometric mean of catch rates varied substantially when using all data records compared to those in the data selection, the optimum statistical models estimated very similar catch rates to those exhibited by the selected data. Thus, the data selection removed much of the 'noise' in the data.

Model 10 with a three-way interaction between skipper, month and block provided the optimum model, indicating that individual skippers vary their fishing location within a year in different ways.

The fishery has two distinct areas on the east and west coast of Tasmania. By including statistical fishing blocks in the analysis, their potential differences were accounted for to some degree. It might be advantageous to conduct separate assessments for the two coastlines as they appear to have different characters, although the amount of data available from the east coast is often far less than that available for the west coast and may prove to be too noisy for a reasonable assessment.

In addition, the annual time step of using quota years may be inappropriate because the effort permitted has greatly varied through the history of the fishery. Inclusion of Month as a factor in the analysis may have alleviated this problem, but it would be worth exploring assessment outcomes using shorter time periods (*e.g.* one or two months) as the base time step.